Brief Contents

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Preface

Welcome to the Eleventh Edition of *Biopsychology*! The Eleventh Edition of *Biopsychology* is a clear, engaging introduction to current biopsychological theory and research. It is intended for use as a primary course material in one- or two-semester courses in Biopsychology—variously titled Biopsychology, Physiological Psychology, Brain and Behavior, Psychobiology, Behavioral Neuroscience, or Behavioral Neurobiology.

The defining feature of *Biopsychology* is its unique combination of biopsychological science and personal, reader-oriented discourse. Instead of presenting the concepts of biopsychology in the usual fashion, the chapters address students directly and interweave the fundamentals of the field with clinical case studies, social issues, personal implications, useful metaphors, and memorable anecdotes.

Key Features in the Eleventh Edition

The following are features that have characterized recent editions of *Biopsychology* and have been maintained or expanded in this edition.

EMPHASIS ON BROAD THEMES The emphasis of *Biopsychology* is "the big picture." Four broad themes are present throughout the chapters and a Themes Revisited section at the end of each chapter briefly summarizes how each theme was developed in that chapter. The four major themes provide excellent topics for essay assignments and exam questions.

EFFECTIVE USE OF CASE STUDIES *Biopsychology* features many carefully selected case studies, which are highlighted in the chapters. These provocative cases stimulate interest, promote retention of the materials, and allow students to learn how biopsychological principles apply to the diagnosis and treatment of brain disorders.

REMARKABLE ILLUSTRATIONS The illustrations in *Biopsychology* are special. Each one was conceptualized and meticulously designed to clarify and reinforce the chapter content by uniquely qualified scientists. John Pinel and his artist/designer wife, Maggie Edwards, created many of the original illustrations from previous editions.

FOCUS ON BEHAVIOR In some biopsychological courseware, the coverage of neurophysiology, neurochemistry, and neuroanatomy subverts the coverage of behavioral research. *Biopsychology* gives top billing to behavior: It stresses that neuroscience is a team effort and that the unique contribution made by biopsychologists to this effort is their behavioral expertise.

EMPHASIS ON THE SCIENTIFIC METHOD *Biopsychology* emphasizes the scientific method. It portrays the scientific method as a means of answering questions that is as applicable in daily life as in the laboratory. And *Biopsychology* emphasizes that being a scientist is fun.

DISCUSSION OF PERSONAL AND SOCIAL IMPLICATIONS Several chapters of *Biopsychology*—-particularly those on eating, sleeping, sex, and drug addiction—carry strong personal and social messages. In these chapters, students are encouraged to consider the relevance of biopsychological research to their lives outside the classroom.

ENGAGING, INSPIRING VOICES Arguably the strongest pedagogical feature of *Biopsychology* is its personal tone. In the previous edition, Barnes and Pinel had addressed students directly and talked to them with warmth, enthusiasm, and good humor about recent advances in biopsychological science. This edition has not changed in this respect.

NEW! EMERGING THEMES For this edition, Barnes and Pinel have identified and highlighted two "emerging themes" throughout the chapters: Themes that they feel are quickly emerging from the biopsychology literature. The Themes Revisited section at the end of each chapter briefly summarizes how each emerging theme was developed in that chapter. The two emerging themes provide excellent topics for essay assignments and exam questions.

New, Expanded, or Updated Coverage in the Eleventh Edition

Biopsychology remains one of the most rapidly progressing scientific fields. Like previous editions, the Eleventh Edition of *Biopsychology* has meticulously incorporated recent developments in the field—it contains more than 950 citations of articles or books that did not appear in the preceding edition. These recent developments have dictated changes to many parts of the chapters. The following list presents some of the content changes to this edition, organized by chapter.

CHAPTER 1: BIOPSYCHOLOGY AS A NEUROSCIENCE

- Introduction of emerging themes appearing in the chapters
- Five new citations

CHAPTER 2: EVOLUTION, GENETICS, AND EXPERIENCE

- Updated schematic illustration of how biopsychologists think about the biology of behavior
- Updated coverage and new key terms related to the topic of gene expression
- Expanded coverage of the topic of transgenerational epigenetics
- Simplified coverage of the evolution of humankind
- Three new key terms: *activators*, *repressors*, *hominins*
- Twenty new citations

CHAPTER 3: ANATOMY OF THE NERVOUS SYSTEM

- Updated and expanded coverage of the functions of glial cells
- Updated anatomical description of the basal ganglia
- Sixteen new citations

CHAPTER 4: NEURAL CONDUCTION AND SYNAPTIC TRANSMISSION

- Improved explanation and coverage of the action potential
- Coverage of the mechanical transmission of membrane potentials
- Two new key terms: *graded potentials*, *voltage-gated ion channels*
- Sixteen new citations

CHAPTER 5: THE RESEARCH METHODS OF BIOPSYCHOLOGY

- Expanded coverage of magnetic-field-based brain-imaging techniques
- Improved explanations of how MRI and fMRI work
- New section on ultrasound-based imaging techniques, such as functional ultrasound imaging
- Introduction of two new transcranial stimulation techniques: transcranial electrical stimulation and transcranial ultrasound stimulation
- Expanded coverage of magnetoencephalography
- Updated coverage of intracellular unit recording
- Expanded and comprehensive coverage of genetic methods, including coverage of gene-editing techniques like the CRISPR/Cas9 method
- Updated coverage on the various ways that fluorescent proteins are used in research
- New case study: The case of the vegetative patient
- New section on the study of functional connectivity
- Nine new key terms: *functional ultrasound imaging*, *transcranial electrical stimulation*, *transcranial ultrasound stimulation*, *gene knockin techniques*, *gene editing techniques*, *CRISPR/Cas9 method*, *resting-state fMRI*, *functional connectivity*, *functional connectome*
- Forty-two new citations

CHAPTER 6: THE VISUAL SYSTEM

- Updated and expanded coverage of modern research on visual system receptive fields
- Updated and expanded coverage of how the concept of a visual system receptive field is changing
- Updated coverage of research on the ventral and dorsal visual streams
- Updated and expanded coverage of the brain pathology associated with prosopagnosia
- One new key term: *occipital face area*
- Thirty-two new citations

CHAPTER 7: SENSORY SYSTEMS, PERCEPTION, AND ATTENTION

- New chapter title
- New chapter introduction, including coverage of some interesting exteroceptive senses only found in particular nonhuman species.
- Updated coverage of the subcortical auditory pathways
- Updated coverage of the organization and functions of the primary auditory cortex
- Updated coverage of the effects of auditory cortex damage
- Introduction of the thermal grid illusion—including a new figure
- Updated coverage of neuropathic pain
- Updated coverage of taste receptors
- Updated coverage of primary gustatory cortex organization
- New module on Perception
- Three new Check It Out features related to perception
- Updated coverage of the neural mechanisms of attention
- Twelve new key terms: *sensation*, *perception*, *periodotopy*, *thermal grid illusion*, *percept*, *perceptual decision making*, *bistable figures*, *phantom percepts*, *Charles Bonnet syndrome*, *binding problem*, *attentional gaze*, *frontal eye field*
- Sixty-one new citations

CHAPTER 8: THE SENSORIMOTOR SYSTEM

- Updated coverage of the primary motor cortex
- Updated coverage of the role of the cerebellum in sensorimotor function
- Updated and expanded coverage of the role of the basal ganglia in sensorimotor function
- More concise coverage of the descending motor pathways
- Updated coverage of the neuroplasticity associated with sensorimotor learning
- New key term: *movement vigor*
- Thirty-seven new citations

CHAPTER 9: DEVELOPMENT OF THE NERVOUS SYSTEM

- Updated coverage of the case of Genie
- Extensive updates to the coverage of stem cells and neurodevelopment
- New figure on the role of glia in neurodevelopment
- Updated coverage of the mechanisms of migration and aggregation of neurons
- Updated coverage of the chemoaffinity hypothesis
- Updated coverage of synapse formation
- Extensive updates to the module on early cerebral development in humans
- New case study written by a self-advocate with autism spectrum disorder
- New case study about the autistic savant Stephen Wiltshire, known by some as the "human camera"
- Coverage of the role of transcription-related errors in individuals with ASD
- Updated coverage of face processing in autism spectrum disorder
- Updated coverage of Williams syndrome, including coverage of face processing differences
- Four new key terms: *subventricular zone*, *radial glial cells*, *radial-glia-mediated migration*, *prenatal period*
- Eighty-three new citations

CHAPTER 10: BRAIN DAMAGE AND NEUROPLASTICITY

- Updated coverage of the mechanisms of ischemic stroke
- New section on traumatic brain injuries
- Coverage of mild traumatic brain injuries
- Updated coverage of chronic traumatic encephalopathy
- Updated discussion of causal factors in epilepsy
- Updated naming of the different types of seizures based on the new diagnostic criteria from the International League Against Epilepsy
- Extensive updates to the section on Parkinson's disease
- Updated and expanded coverage of Huntington's disease
- Updated and expanded coverage of multiple sclerosis
- Extensive updates to the section on Alzheimer's disease—including a new figure
- Five new key terms: *traumatic brain injury (TBI)*, *closed-head TBI*, *subdural hematoma*, *mild TBI*, *alpha-synuclein*
- One hundred and forty-one new citations

CHAPTER 11: LEARNING, MEMORY, AND AMNESIA

- Updated coverage of H.M.
- Updated coverage of the amnesia of Korsakoff's syndrome
- New module: Amnesia after Traumatic Brain Injury: Evidence for Consolidation
- Updated coverage of the role of the hippocampus in consolidation
- Updated and improved coverage of the roles of grid cells
- Updated coverage of the relationship between place cells and grid cells
- New section: The hippocampus as a cognitive map
- Updated coverage of engram cells
- Coverage of the role of hippocampal-prefrontal connections in episodic memory
- Improved and updated coverage of long-term potentiation
- New section on nonsynaptic mechanisms of learning and memory
- Forty-eight new citations

CHAPTER 12: HUNGER, EATING, AND HEALTH

- New section: Evolution of Research on the Role of Hypothalamic Nuclei in Hunger and Satiety
- Updated and extended discussion of the role of hypothalamic circuits and gut peptides in hunger and eating
- Updated discussion of why some people gain weight, whereas others do not
- Updated coverage of leptin, insulin, and the arcuate melanocortin system
- Updated coverage of treatments for overeating
- New key term: *gut microbiome*
- Thirty new citations

CHAPTER 13: HORMONES AND SEX

- New module: Sexual development of brain and behavior
- Updated coverage of the aromatization hypothesis
- Extended and updated discussion of modern perspectives on sex differences in the brain
- Updated coverage of the role of gonadal hormones in female sexual behavior
- Extensive update to the module on sexual orientation and gender identity
- Four new key terms: *lesbian*, *transgender*, *gender identity*, *gender dysphoria*
- Forty-eight new citations

CHAPTER 14: SLEEP, DREAMING, AND CIRCADIAN RHYTHMS

- New module on dreaming
- Three new case studies directly related to the topic of dreaming
- Updated coverage of theories of dreaming
- Updated coverage of recuperation theories of sleep
- Updated coverage of the effects of sleep deprivation in humans
- Updated coverage of interventions for jet lag
- Updated coverage of the effect of shorter sleep times on health
- Two new figures
- One new key term: *lucid dreaming*
- One hundred and twenty-seven new citations

CHAPTER 15: DRUG USE, DRUG ADDICTION, AND THE BRAIN'S REWARD CIRCUITS

- Improved explanation of the relationship between drug withdrawal effects and conditioned compensatory responses
- Extensive update to coverage of nicotine
- Updated coverage of Korsakoff's syndrome
- Extensive update to coverage of marijuana
- Updated coverage of the history of cannabis use
- New discussion of the transgenerational epigenetic effects of drug taking
- Discussion of the current epidemic of opioid abuse
- Three new key terms: *smoking*, *vaping*, *drug craving*
- Eighty new citations

CHAPTER 16: LATERALIZATION, LANGUAGE, AND THE SPLIT BRAIN

- Updated coverage of sex differences in brain lateralization
- Updated coverage of anatomical asymmetries in the brain
- Updated coverage of the evolution of cerebral lateralization
- Updated coverage of the question of when cerebral lateralization evolved
- Twenty-seven new citations

CHAPTER 17: BIOPSYCHOLOGY OF EMOTION, STRESS, AND HEALTH

- Updated coverage of the facial feedback hypothesis
- Updated discussion of whether or not facial expressions are universal
- Thirty-two new citations

CHAPTER 18: BIOPSYCHOLOGY OF PSYCHIATRIC DISORDERS

- Major rewrite of this chapter
- Expanded coverage of all psychiatric disorders profiled in the chapter
- Coverage of the role of genetic, epigenetic, and neural factors for each psychiatric disorder
- Expanded and updated coverage of the discussion of the relative effectiveness of antidepressant medications
- Expanded coverage of theories of bipolar disorder
- Updated coverage of drug therapies for anxiety disorders
- Updated coverage of drug therapies for Tourette's disorder
- One hundred and seven new citations

Pedagogical Learning Aids

Biopsychology has several features expressly designed to help students learn and remember the material:

- **Scan Your Brain** study exercises appear within chapters at key transition points, where students can benefit most from pausing to consolidate material before continuing.
- **Check It Out** demonstrations apply biopsychological phenomena and concepts for students to experience themselves.
- **Themes Revisited** section at the end of each chapter summarizes the ways in which the book's four major themes, and its two emerging themes, relate to that chapter's subject matter.

- **Key Terms** appear in **boldface**, and other important terms of lesser significance appear in *italics*.
- **Appendixes** serve as convenient sources of additional information for students who want to expand their knowledge of selected biopsychology topics.

Ancillary Materials Available with *Biopsychology*

FOR INSTRUCTORS Pearson Education is pleased to offer the following supplements to qualified adopters.

***Test Bank* (9781292352008)** The test bank for the Eleventh Edition of *Biopsychology* comprises more than 2,000 multiple-choice questions, including questions about accompanying brain images. Each item has answer justification, learning objective correlation, difficulty rating, and skill type designation, so that instructors can easily select appropriate questions for their tests.

***Instructor's Manual* (9781292351988)** The instructor's manual contains helpful teaching tools, including at-a-glance grids, activities and demonstrations for the classroom, handouts, lecture notes, chapter outlines, and other valuable course organization material for new and experienced instructors.

***Video Embedded PowerPoint Slides* (9781292401973)** These slides, available in the Instructor's Resource Center, bring highlights of this edition of *Biopsychology* right into the classroom, drawing students into the lecture and providing engaging visuals, and include links to the videos referenced in each chapter.

***Standard Lecture PowerPoint Slides* (9781292351995)** These accessible slides have a more traditional format, with excerpts of the chapter material and artwork, and are available online at www.pearsonglobaleditions.com.

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Pearson Education did a remarkable job of producing the original *Biopsychology*. They shared the dream of a solution that meets the highest standards of pedagogy but is also personal, attractive, and enjoyable. Now they have stepped up to support the conversion of *Biopsychology* to electronic format. Special thanks also go to Kelli Strieby, Matthew Summers, and Lisa Mafrici at Pearson; Marita Bley for her development, editing, and coordination; and Annemarie Franklin at SPi Global for coordinating the production—an excruciatingly difficult and often thankless job.

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To the Student

We have tried to make *Biopsychology* different with content that includes clear, concise, and well-organized explanations of the key points but is still interesting to read—material from which you might suggest suitable sections to an interested friend or relative. To accomplish this goal, we thought about what kind of materials we would have liked when we were students, and we decided to avoid the stern formality and ponderous style of conventional science writing and to focus on ideas of relevance to your personal life.

We want *Biopsychology* to have a relaxed and personal style. In order to accomplish this, we imagined that we were chatting with you as we wrote and that we were telling you—usually over a glass of something—about the interesting things that go on in the field of biopsychology. Imagining these chats kept our writing from drifting back into conventional "textbookese," and it never let us forget that we were writing these materials for you.

As we write these words, we have finished work on this new edition, and now we are waiting with great excitement for *Biopsychology* to be released. There is more excitement around this edition than there has been since the first edition appeared in 1990—this time the excitement is about the release of *Biopsychology* in an online-only format and all the opportunities that it creates for effective teaching. We really hope that you will find this new format easy to use, interesting, and, most importantly, an effective learning tool.

We hope that *Biopsychology* teaches you much of relevance to your personal life and that reading it generates in you the same positive feelings that writing it did in us.

About the Authors

JOHN PINEL obtained his Ph.D. from McGill University in Montreal and worked briefly at the Massachusetts Institute of Technology before taking a faculty position at the University of British Columbia in Vancouver, where he is currently Professor Emeritus. Professor Pinel is an award-winning teacher and the author of more than 200 scientific papers. However, he feels that *Biopsychology* is his major career-related accomplishment: "It ties together everything I love about my job: students, teaching, writing, and research."

STEVEN BARNES obtained his Ph.D. from the University of British Columbia. He then worked as a postdoctoral fellow—first in the Department of Epileptology at the University of Bonn and then in the School of Interactive Arts and Technology at Simon Fraser University. He is currently an Associate Professor of Teaching, and Associate Head of Undergraduate Affairs, in the Department of Psychology at the University of British Columbia.

Steven is well-regarded for his work related to online learning technologies (e.g., the Tapestry Project; see tapestry-tool.com), student mental health and wellbeing, and bipolar disorder (BD). Steven co-directs the Collaborative RESearch Team to study psychosocial issues in BD (CREST.BD, see crestbd.ca), a BD research and knowledge exchange network, which received the 2018 Canadian Institutes for Health Research Gold Leaf Prize for Patient Engagement, Canada's most prestigious recognition for patient engagement in research across all health disciplines.

Steven is the recipient of multiple institutional awards for his teaching, including the prestigious Killam Teaching Prize and the 3M National Teaching Fellowship—the top national award given for teaching in any discipline in any postsecondary institution in Canada.

When he isn't teaching, writing, or doing research, he engages in the production of traditional pieces of visual art as well as interactive electronic artworks—some of which have been exhibited at prominent international venues. He sees his involvement in the creation of this new edition of *Biopsychology* as a complement to everything he loves to do: teaching, writing, visual and interactive art, and research.

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Chapter 1

Biopsychology as a Neuroscience

What Is Biopsychology, Anyway?

Image Source/Alamy Stock Photo

Chapter Overview and Learning Objectives

What Is Biopsychology?	**LO 1.1**	Define and discuss what is meant by *biopsychology*.
	LO 1.2	Discuss the origins of the field of biopsychology.
	LO 1.3	List the six fields of neuroscience that are particularly relevant to biopsychological inquiry.
What Types of Research Characterize the Biopsychological Approach?	**LO 1.4**	Compare the advantages and disadvantages of humans and nonhumans as subjects in biopsychological research.
	LO 1.5	Compare experiments, quasiexperimental studies, and case studies, emphasizing their utility in the study of causal effects.
	LO 1.6	Compare pure and applied research.
What Are the Divisions of Biopsychology?	**LO 1.7**	Describe the division of biopsychology known as physiological psychology.

LO 1.8 Describe the division of biopsychology known as psychopharmacology.

LO 1.9 Describe the division of biopsychology known as neuropsychology.

LO 1.10 Describe the division of biopsychology known as psychophysiology.

LO 1.11 Describe the division of biopsychology known as cognitive neuroscience.

LO 1.12 Describe the division of biopsychology known as comparative psychology.

How Do Biopsychologists Conduct Their Work?

LO 1.13 Explain how converging operations has contributed to the study of Korsakoff's syndrome.

LO 1.14 Explain scientific inference with reference to research on eye movements and the visual perception of motion.

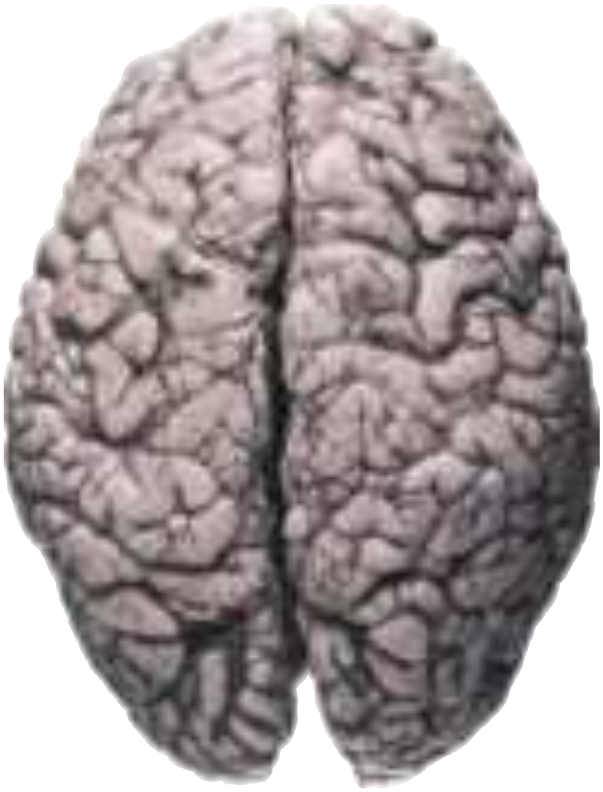
Thinking Critically about Biopsychological Claims

LO 1.15 Define critical thinking and evaluate biopsychological claims.

The appearance of the human brain is far from impressive (see Figure 1.1). The human brain is a squishy, wrinkled, walnut-shaped hunk of tissue weighing about 1.3 kilograms. It looks more like something you might find washed up on a beach than one of the wonders of the world—which it surely is. Despite its disagreeable appearance, the human brain is an amazingly intricate network of **neurons** (cells that receive and transmit electrochemical signals) and many other cell types. Contemplate for a moment the complexity of your own brain's neural circuits. Consider the 90 billion neurons in complex array (Walløe, Pakkenberg & Fabricius, 2014), the estimated 100 trillion connections among them, and the almost infinite number of paths that neural signals can follow through this morass (Zimmer, 2011). The complexity of the human brain is hardly surprising, considering what it can do. An organ capable of creating a *Mona Lisa*, an artificial limb, and a supersonic aircraft; of traveling to the moon and to the depths of the sea; and of experiencing the wonders of an alpine sunset, a newborn infant, and a reverse slam dunk *must* be complex. Paradoxically, **neuroscience** (the scientific study of the nervous system) may prove to be the brain's ultimate challenge: Does the brain have the capacity to understand something as complex as itself (see Gazzaniga, 2010)?

Neuroscience comprises several related disciplines. The primary purpose of this chapter is to introduce you to one of them: biopsychology. Each of this chapter's five modules characterizes the neuroscience of biopsychology in a different way. However, before you proceed to the body of this chapter, we would like to tell you about the case of Jimmie G. (Sacks, 1985), which will give you a taste of the interesting things that lie ahead.

Figure 1.1 The human brain: Appearances can be deceiving!



UHB Trust/The Image Bank/Getty Images

The Case of Jimmie G., the Man Frozen in Time

Jimmie G. was a friendly 49-year-old. He liked to chat about his school days and his time in the navy, both of which he could describe in remarkable detail. Jimmie was an intelligent man with superior abilities in math and science. So why was he a patient in a neurological ward?

When Jimmie talked about his past, there were hints of his problem. When he talked about his school days, he used the past tense; but when he recounted his early experiences in the navy, he switched to the present tense. More worrisome was that he never talked about anything that happened to him after his time in the navy.

Jimmie was tested by eminent neurologist Oliver Sacks, and a few simple questions revealed a curious fact: Jimmie believed he was 19. When asked to describe what he saw in a mirror, Jimmie became so frantic and confused that Dr. Sacks immediately took the mirror out of the room.

Returning a few minutes later, Dr. Sacks was greeted by a once-again cheerful Jimmie, who acted as if he had never seen Sacks before. Indeed, even when Sacks suggested they had met recently, Jimmie was certain they had not.

Then Dr. Sacks asked where Jimmie thought he was. Jimmie replied that all the beds and patients made him think that the place was a hospital. But he couldn't understand why he would be in a hospital. He was afraid that he might have been admitted because he was sick but didn't know it.

Further testing confirmed what Dr. Sacks feared. Although Jimmie had good sensory, motor, and cognitive abilities, he had one terrible problem: He forgot everything that was said or shown to him within a few seconds. Basically, Jimmie could not remember anything that had happened to him since his early 20s, and he was not going to remember anything that happened to him for the rest of his life. Dr. Sacks was stunned by the implications of Jimmie's condition.

Jimmie's situation was heart-wrenching. Unable to form new lasting memories, he was, in effect, a man frozen in time, a man without a recent past and no prospects for a future, stuck in a continuous present, lacking any context or meaning.

Remember Jimmie G.; you will encounter him again later in this chapter.

Four Major Themes of This Text

You will learn many new facts in this text—new findings, concepts, terms, and the like. But more importantly, many years from now, long after you have forgotten most of those facts, you will still be carrying with you productive new ways of thinking. We have selected four of these for special emphasis: Thinking Creatively, Clinical Implications, the Evolutionary Perspective, and Neuroplasticity.

THINKING CREATIVELY ABOUT BIOPSYCHOLOGY. We are all fed a steady diet of biopsychological information, misinformation, and opinion—by television, newspapers, the Internet, friends, relatives, teachers, and so on. As a result, you likely already hold strong views about many of the topics you will encounter in this text. Because these preconceptions are shared by many biopsychological researchers, they have often impeded scientific progress, and some of the most important advances in biopsychological science have been made by researchers who have managed to overcome the restrictive effects of conventional thinking and have taken creative new approaches. Indeed, **thinking creatively** (thinking in productive, unconventional ways) is the cornerstone of any science. In this text, we describe research that involves thinking "outside the box," we try to be creative in our analysis of the research we are presenting, or we encourage you to base your thinking on the evidence rather than on widely accepted views.

CLINICAL IMPLICATIONS. Clinical (pertaining to illness or treatment) considerations are woven through the fabric of biopsychology. There are two aspects to the clinical implications theme: (1) much of what biopsychologists learn about the functioning of a healthy brain comes from studying dysfunctional brains; and (2) many of the discoveries of biopsychologists have relevance for the treatment of brain dysfunction. One of our major focuses is on the interplay between brain dysfunction and biopsychological research.

THE EVOLUTIONARY PERSPECTIVE. Although the events that led to the evolution of the human species can never be determined with certainty, thinking of the environmental pressures that likely led to the evolution of our brains and behavior often leads to important biopsychological insights. This approach is called the **evolutionary perspective**. An important component of the evolutionary perspective is the comparative approach (trying to understand biological phenomena by comparing them in different species). Throughout this text, you will find that we humans have learned much about ourselves by studying species that are related to us through evolution. Indeed, the evolutionary approach has proven to be one of the cornerstones of modern biopsychological inquiry.

NEUROPLASTICITY. Until the early 1990s, most neuroscientists thought of the brain as a three-dimensional array of neural elements "wired" together in a massive network of circuits. The complexity of this "wiring diagram" of the brain was staggering, but it failed to capture one of the brain's most important features. In the past four decades, research has clearly demonstrated that the adult brain is not a static network of neurons: It is a plastic (changeable) organ

that continuously grows and changes in response to an individual's environment and experiences. The discovery of **neuroplasticity** is arguably the single most influential discovery in modern neuroscience. As you will learn, it is a major component of many areas of biopsychological research.

You have probably heard of neuroplasticity. It is a hot topic in the popular media, where it is upheld as a panacea: A means of improving brain function or recovering from brain dysfunction. However, contrary to popular belief, the plasticity of the human brain is not always beneficial. For example, it also contributes to various forms of brain dysfunction (e.g., Tomaszcyk et al., 2014). Later on, you will see examples of both the positive and the negative sides of neuroplasticity.

Emerging Themes of This Text

As you read through this text you will start to see other themes in addition to the ones we outlined for you in the previous section. Many of them you will spot on your own. Here we highlight two "emerging" themes: themes that could become major themes in future editions of this text.

THINKING ABOUT EPIGENETICS. Most people believe their genes (see Chapter 2) control the characteristics they are born with, the person they become, and the qualities of their children and grandchildren. In this text, you will learn that genes are only a small part of what determines who you are. Instead, you are the product of ongoing interactions between your genes and your experiences—such interactions are at the core of a field of study known as **epigenetics**. But epigenetics isn't just about you: We now know that the experiences you have during your lifetime can be passed on to future generations. This is a fundamentally different way of thinking about who we are and how we are tied to both our ancestors and descendants. Epigenetics is currently having a major influence on biopsychological research.

CONSCIOUSNESS. As you will see, this text also examines different aspects of **consciousness** (the perception or awareness of some aspect of one's self or the world) from a biopsychological perspective. Indeed, one major goal of biopsychological research is to establish a better understanding of the neural correlates of consciousness (see Ward, 2013; Blackmore, 2018). To give you a taste of this emerging theme, you will soon appreciate that (1) we are not consciously aware of much of the information we receive from our environments, (2) there are many different states of consciousness, and (3) there can be dramatic alterations in consciousness as a result of brain dysfunction.

What Is Biopsychology?

This module introduces you to the discipline of biopsychology. We begin by exploring the definition and origins of biopsychology. Next, we examine how biopsychology is related to the various other disciplines of neuroscience.

Defining Biopsychology

LO 1.1 Define and discuss what is meant by *biopsychology*.

Biopsychology is the scientific study of the biology of behavior (see Dewsbury, 1991). Some refer to this field as *psychobiology*, *behavioral biology*, or *behavioral neuroscience*; but we prefer the term *biopsychology* because it denotes a biological approach to the study of psychology rather than a psychological approach to the study of biology: Psychology commands center stage in this text. *Psychology* is the scientific study of behavior—the scientific study of all overt activities of the organism as well as all the internal processes that are presumed to underlie them (e.g., learning, memory, motivation, perception, emotion).

What Are the Origins of Biopsychology?

LO 1.2 Discuss the origins of the field of biopsychology.

The study of the biology of behavior has a long history, but biopsychology did not develop into a major neuroscientific discipline until the 20th century. Although it is not possible to specify the exact date of biopsychology's birth, the publication of *The Organization of Behavior* in 1949 by Donald Hebb played a key role in its emergence (see Brown & Milner, 2003). In his book, Hebb developed the first comprehensive theory of how complex psychological phenomena, such as perceptions, emotions, thoughts, and memories, might be produced by brain activity. Hebb's theory did much to discredit the view that psychological functioning is too complex to have its roots in the physiology and chemistry of the brain. Hebb based his theory on experiments involving both human and nonhuman animals, on clinical case studies, and on logical arguments developed from his own insightful observations of daily life. This eclectic approach has become a hallmark of biopsychological inquiry.

In comparison to physics, chemistry, and biology, biopsychology is an infant—a healthy, rapidly growing infant, but an infant nonetheless. In this text, you will reap the benefits of biopsychology's youth. Because biopsychology does not have a long history, you will be able to move quickly to the excitement of modern research.

How Is Biopsychology Related to the Other Disciplines of Neuroscience?

LO 1.3 List the six fields of neuroscience that are particularly relevant to biopsychological inquiry.

Neuroscience is a team effort, and biopsychologists are important members of the team (see Albright, Kandel, & Posner, 2000; Kandel & Squire, 2000). Biopsychology can be further characterized by its relation to other neuroscientific disciplines.

Biopsychologists are neuroscientists who bring to their research a knowledge of behavior and of the methods of behavioral research. It is their behavioral orientation and expertise that make their contribution to neuroscience unique (see Cacioppo & Decety, 2009). You will be able to better appreciate the importance of this contribution if you consider that the ultimate purpose of the nervous system is to produce and control behavior (see Grillner & Dickinson, 2002). Think about it.

Biopsychology is an integrative discipline. Biopsychologists draw together knowledge from the other neuroscientific disciplines and apply it to the study of behavior. The following are a few of the disciplines of neuroscience that are particularly relevant to biopsychology:

- **Neuroanatomy**. The study of the structure of the nervous system (see Chapter 3).
- **Neurochemistry**. The study of the chemical bases of neural activity (see Chapters 4 and 15).
- **Neuroendocrinology**. The study of interactions between the nervous system and the endocrine system (see Chapters 13 and 17).
- **Neuropathology**. The study of nervous system dysfunction (see Chapters 10 and 18).
- **Neuropharmacology**. The study of the effects of drugs on neural activity (see Chapters 4, 15, and 18).
- **Neurophysiology**. The study of the functions and activities of the nervous system (see Chapter 4).

What Types of Research Characterize the Biopsychological Approach?

Biopsychology is broad and diverse. Biopsychologists study many different phenomena, and they approach their research in many different ways. This module discusses three major dimensions along which biopsychological research may vary: It can involve either human or nonhuman subjects, it can take the form of either formal experiments or nonexperimental studies, and it can be either pure or applied.

Human and Nonhuman Subjects

LO 1.4 Compare the advantages and disadvantages of humans and nonhumans as subjects in biopsychological research.

Both human and nonhuman animals are the subjects of biopsychological research. Of the nonhumans, mice and rats are the most common subjects; however, cats, dogs, and nonhuman primates are also commonly studied.

Humans have several advantages over other animals as experimental subjects of biopsychological research: They can follow instructions, they can report their subjective experiences, and their cages are easier to clean. Of course, we are joking about the cages, but the joke does serve to draw attention to one advantage humans have over other species of experimental subjects: Humans are often cheaper. Because only the highest standards of animal care are acceptable, the cost of maintaining an animal laboratory can be prohibitive for all but the most well-funded researchers.

Of course, the greatest advantage humans have as subjects in a field aimed at understanding the intricacies of human brain function is that they have human brains. In fact, you might wonder why biopsychologists would bother studying nonhuman subjects at all. The answer lies in the evolutionary continuity of the brain. The brains of humans are similar in fundamental ways to the brains of other mammals—they differ mainly in their overall size and the extent of their cortical development. In other words, the differences between the brains of humans and those of related species are more quantitative than qualitative, and thus many of the principles of human brain function can be clarified by the study of nonhumans (see Hofman, 2014; Katzner & Weigelt, 2013; Krubitzer & Stolzenberg, 2014).

One major difference between human and nonhuman subjects is that humans volunteer to be subjects. To emphasize this point, human subjects are more commonly referred to as *participants* or *volunteers*.

Nonhuman animals have three advantages over humans as subjects in biopsychological research. The first is that the brains and behavior of nonhuman subjects are simpler than those of human participants. Hence, the study of nonhuman species is often more likely to reveal fundamental brain–behavior interactions. The second advantage is that insights frequently arise from the **comparative approach**, the study of biological processes by comparing different species. For example, comparing the behavior of species that do not have a cerebral cortex with the behavior of species that do can provide valuable clues about cortical function. The third advantage is that it is possible to

conduct research on laboratory animals that, for ethical reasons, is not possible with human participants. This is not to say that the study of nonhuman animals is not governed by a strict code of ethics (see Blakemore et al., 2012)—it is. However, there are fewer ethical constraints on the study of laboratory species than on the study of humans.

In our experience, most biopsychologists display considerable concern for their subjects, whether they are of their own species or not; however, ethical issues are not left to the discretion of the individual researcher. All biopsychological research, whether it involves human participants or nonhuman subjects, is regulated by independent committees according to strict ethical guidelines: "Researchers cannot escape the logic that if the animals we observe are reasonable models of our own most intricate actions, then they must be respected as we would respect our own sensibilities" (Ulrich, 1991, p. 197).

If you are concerned about the ethics of biopsychological research on nonhuman animals, you aren't alone. Both of us wrestle with various aspects of it. For example, a recurring concern we both have is whether the potential benefits of a research study outweigh the stress induced in the nonhuman subjects.

When people are asked for their opinion on nonhuman animal research, most fall into one of two camps: (1) Those in support of animal research—if and only if both the suffering of animals is minimized and the potential benefits to humankind cannot be obtained by other methods, or (2) those that are opposed to animal research—because it causes undue stress that is not outweighed by the potential benefits to humankind.

Journal Prompt 1.1

What are your initial feelings about biopsychological research on nonhuman animals? If you are sympathetic to one of the two aforementioned camps, explain your reasoning.

Because biopsychological research using nonhuman subjects is controversial, it first has to be approved by a panel of individuals from a variety of backgrounds and with different world views. These *nonhuman animal ethics committees* are tasked with very difficult decisions. Accordingly, it is usually the case that these committees will ask the researchers proposing a particular study to provide additional information or further justification before they approve their research.

Nonhuman animal ethics committees emphasize consideration of the so-called "three R's": Reduction, Refinement, and Replacement. Reduction refers to efforts to reduce the numbers of animals used in research. Refinement refers to refining research studies or the way animals are cared for, so as to reduce suffering. Providing animals with better living conditions is one example of refinement. Finally, replacement refers to the replacing of studies using animal subjects with alternate techniques, such as experimenting on cell cultures or using computer models.

One of the earliest examples of replacement is the now ubiquitous crash-test dummy in the auto industry. Prior to the advent of the crash test dummy, live pigs were sometimes used as passengers in automobile crash tests. This example of replacement makes an important point about how notions of what is ethically acceptable in animal experimentation are in constant flux: Now that dummies are a viable alternative, nobody would be in favor of using pigs for crash tests. The recent development of complex computer models of nonhuman and human brains (see Frackowiak & Markram, 2015) might change the very nature of biopsychological research in your lifetime.

Experiments and Nonexperiments

LO 1.5 Compare experiments, quasiexperimental studies, and case studies, emphasizing their utility in the study of causal effects.

Biopsychological research involves both experiments and nonexperimental studies. Two common types of nonexperimental studies are quasiexperimental studies and case studies.

EXPERIMENTS. The experiment is the method used by scientists to study causation, that is, to find out what causes what. As such, it has been almost single-handedly responsible for the knowledge that is the basis for our modern way of life. It is paradoxical that a method capable of such complex feats is so simple. To conduct an experiment involving living subjects, the experimenter first designs two or more conditions under which the subjects will be tested. Usually, a different group of subjects is tested under each condition (**between-subjects design**), but sometimes it is possible to test the same group of subjects under each condition (**within-subjects design**). The experimenter assigns the subjects to conditions, administers the treatments, and measures the outcome in such a way that there is only one relevant difference between the conditions being compared. This difference between the conditions is called the **independent variable**. The variable measured by the experimenter to assess the effect of the independent variable is called the **dependent variable**. If the experiment is done correctly, any differences in the dependent variable between the conditions must have been caused by the independent variable.

Why is it critical that there be no differences between conditions other than the independent variable? The reason is that when there is more than one difference that could affect the dependent variable, it is difficult to determine whether it was the independent variable or the unintended difference—called a **confounded variable**—that led to the observed effects on the dependent variable. Although the experimental method is conceptually simple, eliminating all confounded

variables can be quite difficult. Readers of research papers must be constantly on the alert for confounded variables that have gone unnoticed by the experimenters.

An experiment by Lester and Gorzalka (1988) illustrates the prevention of confounded variables with good experimental design. The experiment was a demonstration of the **Coolidge effect** (see Lucio et al., 2014; Tlachi-López et al., 2012). The Coolidge effect is the fact that a copulating male who becomes incapable of continuing to copulate with one sex partner can often recommence copulating with a new sex partner (see Figure 1.2). Before your imagination starts running wild, we should mention that the subjects in Lester and Gorzalka's experiment were hamsters, not university students.

Figure 1.2 President Calvin Coolidge and Mrs. Grace Coolidge. Many students think the Coolidge effect is named after a biopsychologist named Coolidge. In fact, it is named after President Calvin Coolidge, of whom the following story is told. (If the story isn't true, it should be.)

During a tour of a poultry farm, Mrs. Coolidge inquired of the farmer how his farm managed to produce so many eggs with such a small number of roosters. The farmer proudly explained that his roosters performed their duty dozens of times each day.

"Perhaps you could point that out to Mr. Coolidge," replied the First Lady in a pointedly loud voice.

The President, overhearing the remark, asked the farmer, "Does each rooster service the same hen each time?"

"No," replied the farmer, "there are many hens for each rooster."

"Perhaps you could point that out to Mrs. Coolidge," replied the President.

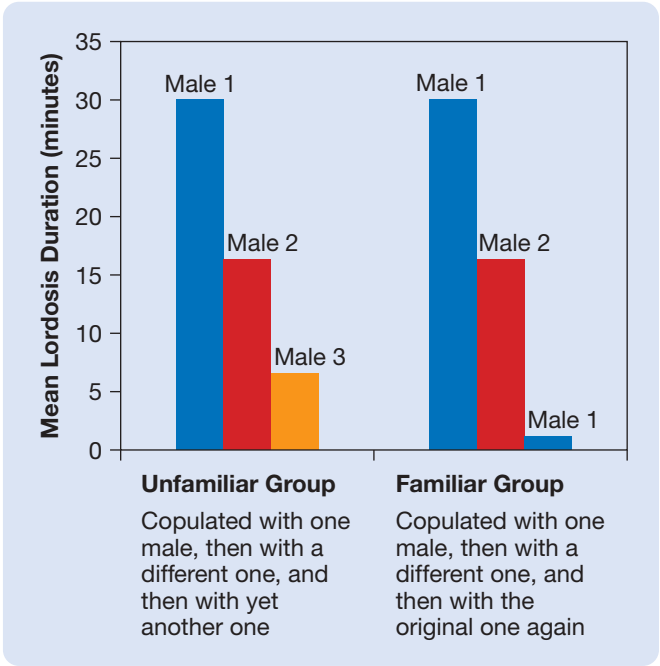
Bettmann/Getty Images

Lester and Gorzalka argued that the Coolidge effect had not been demonstrated in females because it is more difficult to conduct well-controlled Coolidge-effect experiments with females—not because females do not display a Coolidge effect. The confusion, according to Lester and Gorzalka, stemmed from the fact that the males of most mammalian species become sexually fatigued more readily than the females. As a result, attempts to demonstrate the Coolidge effect in females are almost always confounded by the fatigue of the males. When, in the midst of copulation, a female is provided with a new sex partner, the increase in her sexual receptivity could be either a legitimate Coolidge effect or a reaction to the greater vigor of the new male. Because female mammals usually display little sexual fatigue, this confounded variable is not a serious problem in demonstrations of the Coolidge effect in males.

Lester and Gorzalka devised a clever procedure to control for this confounded variable. At the same time a female subject was copulating with one male (the familiar male), the other male to be used in the test (the unfamiliar male) was copulating with another female. Then both males were given a rest while the female was copulating with a third male. Finally, the female subject was tested with either the familiar male or the unfamiliar male. The dependent variable was the amount of time that the female displayed **lordosis** (the arched-back, rump-up, tail-diverted posture of female rodent sexual receptivity) during each sex test. As Figure 1.3 illustrates, the females responded more vigorously to the unfamiliar males than they did to the familiar males during the third test, despite the fact that both the unfamiliar and familiar males were equally fatigued and both mounted the females with equal vigor. The purpose of this example—in case you have forgotten—is to illustrate the critical role played by good experimental design in eliminating confounded variables.

QUASIEXPERIMENTAL STUDIES. It is not possible for biopsychologists to bring the experimental method to bear on all problems of interest to them. Physical or ethical impediments frequently make it impossible to assign subjects to particular conditions or to administer particular conditions to the subjects who have been assigned to them. For example, experiments assessing whether frequent marijuana use causes brain dysfunction are not feasible because it would be unethical to assign a human to a condition that involves years of frequent marijuana use. (Some of you may be more concerned about the ethics of assigning humans to a control condition that involves many years of *not* getting high.) In such prohibitive situations, biopsychologists sometimes conduct **quasiexperimental studies**—studies of groups of subjects who have been exposed to the conditions of interest in

Figure 1.3 The experimental design and results of Lester and Gorzalka (1988). On the third test, the female hamsters were more sexually receptive to an unfamiliar male than they were to the male with which they had copulated on the first test.



Based on Lester, G. L. L., & Gorzalka, B. B. (1988)

the real world. These studies have the appearance of experiments, but they are not true experiments because potential confounded variables have not been controlled—for example, by the random assignment of subjects to conditions.

In the popular press, quasiexperiments are often confused with experiments. Not a week goes by where one of us doesn't read a news article about how an "experiment" has shown something in human participants, when in reality the so-called experiment is actually a quasiexperiment.

Understanding the distinction between quasiexperiments and experiments is very important. Experiments can tell us whether an independent variable causes a change in a dependent variable (assuming that the experimenter has controlled for all confounding variables); quasiexperiments can tell us only that two variables are correlated with one another. For example, in interpreting experiments we can reach causal conclusions like "frequent alcohol consumption causes brain damage." In contrast, quasiexperimental studies can tell us only that "frequent alcohol use is associated with brain damage."

The importance of thinking clearly about quasiexperimental studies is illustrated by a study that compared 100 detoxified males who had previously been heavy drinkers of alcohol with 50 male nondrinkers (Acker et al., 1984). Overall, those who had been heavy drinkers performed more poorly on various tests of perceptual, motor, and cognitive ability, and their brain scans revealed extensive brain damage. Although this might seem like an experiment, it is not. It is a quasiexperimental study: Because the participants themselves decided which group they would be in—by drinking alcohol or not—the researchers had no means of ensuring that exposure to alcohol was the only variable that distinguished the two groups. Can you think of differences other than exposure to alcohol that could reasonably be expected to exist between a group of heavy drinkers and a group of abstainers—differences that could have contributed to the neuroanatomical or intellectual differences that were observed between them? There are several. For example, heavy drinkers as a group tend to be more poorly educated, more prone to accidental head injury, more likely to use other drugs, and more likely to have poor diets. Accordingly, although quasiexperimental studies have revealed that people who are heavy drinkers tend to have more brain damage than abstainers, such studies cannot prove that it was caused by the alcohol.

Have you forgotten the case of Jimmie G.? Jimmie's condition was a product of heavy alcohol consumption.

CASE STUDIES. Studies that focus on a single subject, or very small number of subjects, are called **case studies**. Such studies are rarely concerned with having control subjects. Rather, their focus is on providing a more in-depth picture than that provided by an experiment or a quasiexperimental study, and they are an excellent source of testable hypotheses. However, there is a major problem with all case studies: their **generalizability**—the degree to which their results can be applied to other cases. Because individuals differ from one another in both brain function and behavior, it is important to be skeptical of any biopsychological theory based entirely on a few case studies.

Pure and Applied Research

LO 1.6 Compare pure and applied research.

Biopsychological research can be either pure or applied. Pure research and applied research differ in a number of respects, but they are distinguished less by their own attributes than by the motives of the researchers involved in their pursuit. **Pure research** is motivated primarily by the curiosity of the researcher—it is done solely for the purpose of acquiring knowledge. In contrast, **applied research** is intended to bring about some direct benefit to humankind.

Many scientists believe that pure research will ultimately prove to be of more practical benefit than applied research. Their view is that applications flow readily from an understanding of basic principles and that attempts to move directly to application without first gaining a basic understanding are shortsighted. Of course, it is not necessary for a research project to be completely pure or completely applied; many research programs have elements of both approaches. Moreover, pure research often becomes the topic of **translational research**: research that aims to translate the findings of pure research into useful applications for humankind (see Howells, Sena, & Macleod, 2014).

One important difference between pure and applied research is that pure research is more vulnerable to the vagaries of political regulation because politicians and the voting public have difficulty understanding why research of no immediate practical benefit should be supported. If the decision were yours, would you be willing to grant millions of dollars to support the study of squid *motor neurons* (neurons that control muscles), learning in recently hatched geese, the activity of single nerve cells in the visual systems of monkeys, the hormones released by the *hypothalamus* (a small neural structure at the base of the brain) of pigs and sheep, or the functions of the *corpus callosum* (the large neural pathway that connects the left and right halves of the brain)? Which, if any, of these projects would you consider worthy of support? Each of these seemingly esoteric projects was supported, and each earned a Nobel Prize.

Table 1.1 provides a timeline of some of the Nobel Prizes awarded for research related to the brain and behavior. The purpose of this table is to give you a general sense of the official recognition that behavioral and brain research has received, not to have you memorize the list. You will learn later in the chapter that, when it comes to evaluating science, the Nobel Prize Committees have not been infallible.

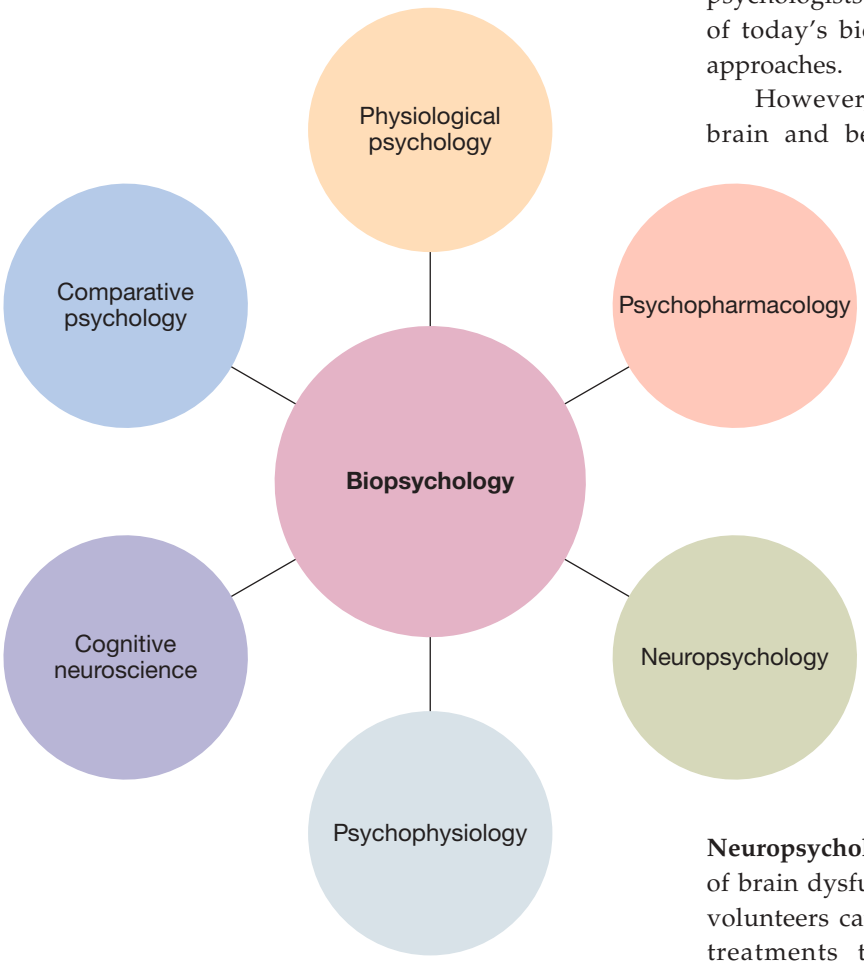
What Are the Divisions of Biopsychology?

As you have just learned, biopsychologists conduct their research in a variety of fundamentally different ways. Biopsychologists who take the same approaches to their research tend to publish their research in the same journals, attend the same scientific meetings, and belong to the same professional societies. The particular approaches to biopsychology that have flourished and grown have gained wide recognition as separate divisions of biopsychological research. The purpose of this module is to give you a clearer sense of biopsychology and its diversity by describing six of its major divisions (see Figure 1.4): (1) physiological psychology, (2) psychopharmacology, (3) neuropsychology, (4) psychophysiology, (5) cognitive neuroscience, and (6) comparative psychology. For simplicity, they are presented as distinct approaches, but there is much overlap among them, and many biopsychologists regularly follow more than one approach.

Table 1.1 Nobel prizes specifically related to the nervous system or behavior.

Nobel Winner(s)	Date	Accomplishment
Ivan Pavlov	1904	Research on the physiology of digestion
Camillo Golgi and Santiago Ramón y Cajal	1906	Research on the structure of the nervous system
Charles Sherrington and Edgar Adrian	1932	Discoveries about the functions of neurons
Henry Dale and Otto Loewi	1936	Discoveries about the transmission of nerve impulses
Joseph Erlanger and Herbert Gasser	1944	Research on the functions of single nerve fibers
Walter Hess	1949	Research on the role of the brain in behavior
Egas Moniz	1949	Development of the prefrontal lobotomy
Georg von Békésy	1961	Research on the auditory system
John Eccles, Alan Hodgkin, and Andrew Huxley	1963	Research on the ionic basis of neural transmission
Ragnar Granit, Haldan Hartline, and George Wald	1967	Research on the chemistry and physiology of vision
Bernard Katz, Ulf von Euler, and Julius Axelrod	1970	Discoveries related to synaptic transmission
Karl Von Frisch, Konrad Lorenz, and Nikolaas Tinbergen	1973	Studies of animal behavior
Roger Guillemin and Andrew Schally	1977	Discoveries related to hormone production by the brain
Herbert Simon	1979	Research on human cognition
Roger Sperry	1981	Research on separation of the cerebral hemispheres
David Hubel and Torsten Wiesel	1981	Research on neurons of the visual system
Rita Levi-Montalcini and Stanley Cohen	1986	Discovery and study of nerve growth factors
Erwin Neher and Bert Sakmann	1991	Research on ion channels
Alfred Gilman and Martin Rodbell	1994	Discovery of G-protein–coupled receptors
Arvid Carlsson, Paul Greengard, and Eric Kandel	2000	Discoveries related to synaptic transmission
Linda Buck and Richard Axel	2004	Research on the olfactory system
John O'Keefe, May-Britt Moser, and Edvard Moser	2014	Research on the brain's system for recognizing locations
Jeffrey Hall, Michael Rosbach, and Michael Young	2017	Discoveries related to the molecular mechanisms controlling the circadian rhythm

Figure 1.4 The six major divisions of biopsychology.



Physiological Psychology

LO 1.7 **Describe the division of biopsychology known as physiological psychology.**

Physiological psychology is the division of biopsychology that studies the neural mechanisms of behavior through the direct manipulation and recording of the brain in controlled experiments—surgical and electrical methods are most common. The subjects of physiological psychology research are almost always laboratory animals because the focus on direct brain manipulation and controlled experiments precludes the use of human participants in most instances. There is also a tradition of pure research in physiological psychology; the emphasis is usually on research that contributes to the development of theories of the neural control of behavior rather than on research of immediate practical benefit.

Psychopharmacology

LO 1.8 **Describe the division of biopsychology known as psychopharmacology.**

Psychopharmacology is similar to physiological psychology except that it focuses on the manipulation of neural activity and behavior with drugs. In fact, many of the early psychopharmacologists were simply physiological psychologists who moved into drug research, and many of today's biopsychologists identify closely with both approaches.

However, the study of the effects of drugs on brain and behavior has become so specialized that psychopharmacology is regarded as a separate discipline. A substantial portion of psychopharmacological research is applied. Although drugs are sometimes used by psychopharmacologists to study the basic principles of brain–behavior interaction, the purpose of many psychopharmacological experiments is to develop therapeutic drugs (see Chapter 18) or to reduce drug abuse (see Chapter 15). Psychopharmacologists study the effects of drugs on laboratory species—and on humans, if the ethics of the situation permits it.

Neuropsychology

LO 1.9 **Describe the division of biopsychology known as neuropsychology.**

Neuropsychology is the study of the psychological effects of brain dysfunction in human patients. Because human volunteers cannot ethically be exposed to experimental treatments that endanger normal brain function, neuropsychology deals almost exclusively with case studies and quasiexperimental studies of patients with brain dysfunction resulting from disease, accident, or neurosurgery. The outer layer of the cerebral hemispheres—the **cerebral cortex**—is most likely to be damaged by accident or surgery; this is one reason why neuropsychology has focused on this important part of the human brain.

Neuropsychology is the most applied of the biopsychological subdisciplines; the neuropsychological assessment of human patients, even when part of a program of pure research, is always done with an eye toward benefiting them in some way. Neuropsychological tests facilitate diagnosis and thus help the attending physician prescribe effective treatments (see Benton, 1994). They can also be an important basis for patient care and counseling; Kolb and Whishaw (1990) described such an application in the case study of Mr. R.

The Case of Mr. R., the Student with a Brain Injury Who Switched to Architecture

Mr. R. was a 21-year-old honors student at a university. One day he was involved in a car accident in which he struck his head against the dashboard. Following the accident, Mr. R's grades began to

decline; his once exceptional academic performance was now only average. He seemed to have particular trouble completing his term papers. Finally, after a year of struggling academically, he went for a neuropsychological assessment. The findings were striking.

Mr. R. turned out to be one of roughly one-third of left-handers whose language functions are represented in the right hemisphere of their brain, rather than in their left hemisphere. Furthermore, although Mr. R. had a superior IQ score, his verbal memory and reading speed were below average—something that is quite unusual for a person who had been so strong academically.

The neuropsychologists concluded that he may have suffered some damage to his right temporal lobe during the car accident, which would help explain his diminished language skills. The neuropsychologists also recommended that R. pursue a field that didn't require superior verbal memory skills. Following his exam and based on the recommendation of his neuropsychologists, Mr. R. switched majors and began studying architecture with substantial success.

Psychophysiology

LO 1.10 Describe the division of biopsychology known as psychophysiology.

Psychophysiology is the division of biopsychology that studies the relation between physiological activity and psychological processes in humans. Because the subjects of psychophysiological research are humans, psychophysiological recording procedures are typically noninvasive; that is, the physiological activity is recorded from the surface of the body. The usual measure of brain activity is the scalp **electroencephalogram (EEG)** (see Chapter 5). Other common psychophysiological measures are muscle tension, eye movement, and several indicators of autonomic nervous system activity (e.g., heart rate, blood pressure, pupil dilation, and electrical conductance of the skin). The **autonomic nervous system (ANS)** is the division of the nervous system that regulates the body's inner environment (see Chapter 3).

Most psychophysiological research focuses on understanding the physiology of psychological processes, such as attention, emotion, and information processing, but there have been some interesting clinical applications of the psychophysiological method. For example, psychophysiological experiments have indicated that people with schizophrenia have difficulty smoothly tracking a moving object with their eyes (see Meyhöfer et al., 2014)—see Figure 1.5.

Journal Prompt 1.2

What implications could the finding that people with schizophrenia have difficulty smoothly tracking moving objects have for the diagnosis of schizophrenia? (For a discussion of schizophrenia, see Chapter 18.)

Cognitive Neuroscience

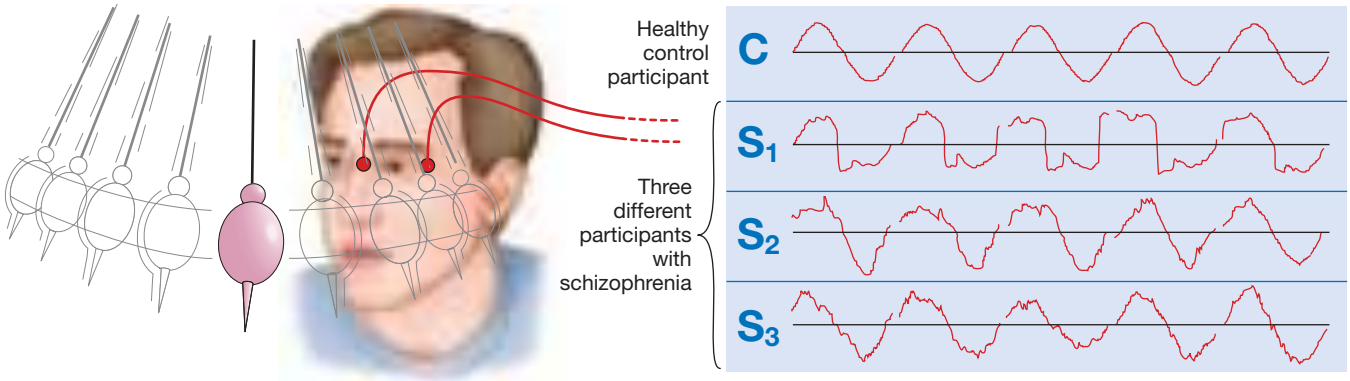
LO 1.11 Describe the division of biopsychology known as cognitive neuroscience.

Cognitive neuroscience is the youngest division of biopsychology. Cognitive neuroscientists study the neural bases of **cognition**, a term that generally refers to higher intellectual processes such as thought, memory, attention, and complex perceptual processes (see Gutchess, 2014; Raichle, 2008). Because of its focus on cognition, most cognitive neuroscience research involves human participants, and because of its focus on human participants, its methods tend to be noninvasive, rather than involving penetration or direct manipulation of the brain.

The major method of cognitive neuroscience is *functional brain imaging*: recording images of the activity of the living human brain (see Chapter 5) while a participant is engaged in a particular mental activity. For example, Figure 1.6 shows that the visual areas of the left and right cerebral cortex at the back of the brain became active when the participant viewed a flashing light.

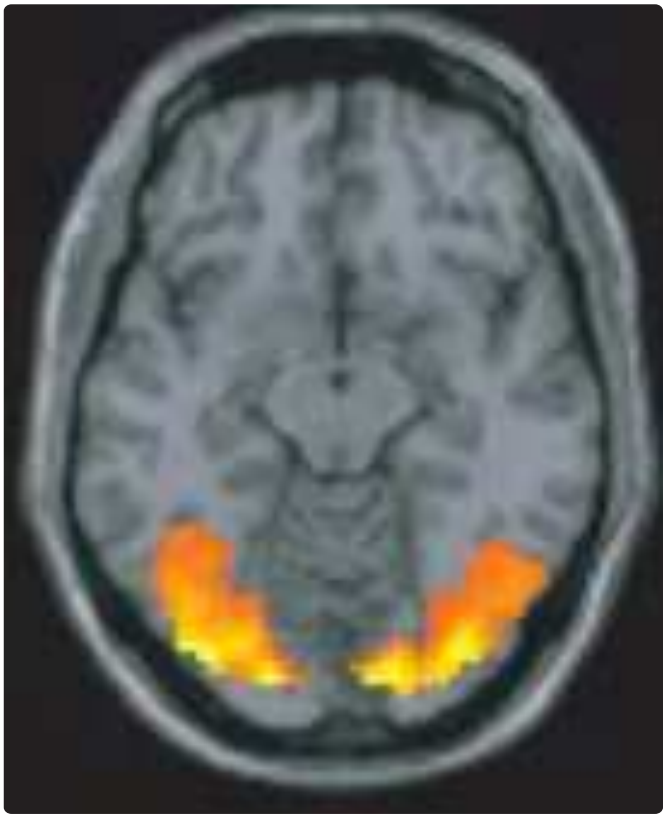
Because the theory and methods of cognitive neuroscience are so complex and pertinent to so many fields, cognitive neuroscience research often involves interdisciplinary

Figure 1.5 Visual tracking of a pendulum by a healthy control participant (top) and three participants with schizophrenia.



Based on Iacono, W. G., & Koenig, W. G. (1983).

Figure 1.6 Functional brain imaging is the major method of cognitive neuroscience. This image—taken from the top of the head with the participant lying on her back—reveals the locations of high levels of neural activity at one level of the brain as the participant viewed a flashing light. The red and yellow areas indicate high levels of activity in the visual cortex at the back of the brain. (Courtesy of Dr. Todd Handy, Department of Psychology, University of British Columbia.)



Todd C. Handy/University of British Columbia Department of Psychology

collaboration among many researchers with different types of training. Biopsychologists, cognitive psychologists, social psychologists, economists, computing and mathematics experts, and various types of neuroscientists commonly contribute to the field. Cognitive neuroscience research sometimes involves noninvasive electrophysiological recording, and it sometimes focuses on patients with brain dysfunction; in these cases, the boundaries between cognitive neuroscience and psychophysiology and neuropsychology, respectively, are blurred.

Comparative Psychology

LO 1.12 Describe the division of biopsychology known as comparative psychology.

Although most biopsychologists study the neural mechanisms of behavior, there is more to biopsychology than neural mechanisms. A biopsychologist should never lose sight of the fact that the purpose of their research is to understand the integrated behavior of the whole animal. The last division of biopsychology that we describe here is one that focuses on the behavior of animals in their natural environments. This division is **comparative psychology**.

Comparative psychologists compare the behavior of different species in order to understand the evolution, genetics, and adaptiveness of behavior. Some comparative psychologists study behavior in the laboratory; others engage in **ethological research**—the study of behavior in an animal's natural environment.

As a reminder, the purpose of this module was to demonstrate the diversity of biopsychology by describing six of its major divisions; these are summarized for you in Table 1.2. You will see all six of these divisions in action in subsequent chapters.

Table 1.2 The six major divisions of biopsychology with examples of how they have approached the study of memory.

Division of Biopsychology	Example from Memory Research
Physiological psychology: study of the neural mechanisms of behavior by manipulating the nervous systems of nonhuman animals in controlled experiments	Physiological psychologists have studied the contributions of one brain structure, the hippocampus, to memory by surgically removing it in rats and assessing their ability to perform various memory tasks.
Psychopharmacology: study of the effects of drugs on the brain and behavior	Psychopharmacologists have tried to improve the memory of Alzheimer's patients by administering drugs that alter brain chemistry.
Neuropsychology: study of the psychological effects of brain dysfunction in human patients	Neuropsychologists have shown that patients with damage to the hippocampus and surrounding structures are incapable of forming new long-term memories.
Psychophysiology: study of the relation between physiological activity and psychological processes in human volunteers by noninvasive physiological recording	Psychophysiologists have shown that familiar faces elicit the usual changes in autonomic nervous system activity even when patients with brain damage report that they do not recognize a face.
Cognitive neuroscience: study of the neural mechanisms of human cognition, largely through the use of functional brain imaging	Cognitive neuroscientists have used brain-imaging technology to observe the changes that occur in various parts of the brain while human volunteers perform memory tasks.
Comparative psychology: study of the evolution, genetics, and adaptiveness of behavior, largely through the use of the comparative method	Comparative psychologists have shown that species of birds that cache their seeds tend to have larger hippocampi, confirming that the hippocampus is involved in memory for location.

Scan Your Brain

To see if you are acquainted with the main premises of biopsychology and allied disciplines, fill in each of the following blanks with the most appropriate terms. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. _____ is a branch of psychology that uses data from patients with brain damage to understand structure and function of the human brain.
2. Over the past few decades, researchers have realized that the adult brain connections are not static but changeable in response to the individual's genes and experiences. This is known as _____.
3. In a _____ design, participants are placed into different groups and exposed to different experimental conditions.
4. Studies that focus on a single participant rather than a group of participants are called _____.
5. The major method of cognitive neuroscience is _____, recording images of the activity of the living human brain.
6. _____ is a branch of biopsychology that studies genetic, evolutionary, and behavior differences across species.

Scan Your Brain answers: (1) Neuropsychology, (2) neuroplasticity, (3) between-subjects, (4) case studies, (5) functional brain imaging, (6) Evolutionary behavioral genetics.

How Do Biopsychologists Conduct Their Work?

This module explains how biopsychologists typically conduct their work. First, you will learn how biopsychologists collaborate with one another, and the importance of such collaboration in advancing a field of research. Second, you will learn about how biopsychologists make inferences about brain function that is not directly observable. These are important components of biopsychological research, and you will see in the next module what goes wrong when such collaboration and scientific inference are thrown by the wayside.

Converging Operations: How Do Biopsychologists Work Together?

LO 1.13 Explain how converging operations has contributed to the study of Korsakoff's syndrome.

Because each of the six biopsychological approaches to research has its own particular strengths and shortcomings and because the mechanisms by which the brain controls behavior are so complex, major biopsychological issues are rarely resolved by a single experiment or even by a series of experiments taking the same general approach. Progress is most likely when different approaches are focused on a single problem in such a way that the strengths of one approach compensate for the weaknesses of the others; this combined approach is called **converging operations** (see Thompson, 2005).

Consider, for example, the relative strengths and weaknesses of neuropsychology and physiological psychology in the study of the psychological effects of damage to the human cerebral cortex. In this instance, the strength of the neuropsychological approach is that it deals directly with human patients; its weakness is that its focus on human patients precludes experiments. In contrast, the strength of the physiological psychology approach is that it can use the power of experimental research on nonhuman animals; its weakness is that the relevance of research on laboratory animals to human brain damage is always open to question (see Couzin-Frankel, 2013; Reardon, 2016). Clearly these two approaches complement each other well; together they can answer questions that neither can answer individually.

To examine converging operations in action, let's return to the case of Jimmie G. The neuropsychological disorder from which Jimmie suffered was first described in the late 19th century by Sergei Korsakoff, a Russian physician, and subsequently became known as **Korsakoff's syndrome**. The primary symptom of Korsakoff's syndrome is severe memory loss, which is made all the more heartbreaking—as you have seen in Jimmie G.'s case—by the fact that its sufferers are often otherwise quite capable. Because Korsakoff's syndrome commonly occurs in heavy drinkers of alcohol, it was initially believed to be a direct consequence of the toxic effects of alcohol on the brain. This conclusion proved to be a good illustration of the inadvisability of inferring causality from the results of quasiexperimental studies. Subsequent research showed that Korsakoff's syndrome is largely caused by the brain damage associated with *thiamine* (vitamin B_1) deficiency.

Journal Prompt 1.3

Korsakoff's syndrome accounts for approximately 10 percent of adult dementias in the United States. Despite its relatively high prevalence, few people have heard of it. Why do you think this is the case?

The first support for the thiamine-deficiency interpretation of Korsakoff's syndrome came from the discovery of the syndrome in malnourished persons who consumed little or no alcohol. Additional support came from experiments in which thiamine-deficient rats were compared with otherwise identical groups of control rats. The thiamine-deficient rats displayed memory deficits and patterns of brain damage similar to those observed in many people who had been heavy drinkers of alcohol (Mumby, Cameli, & Glenn, 1999). Such people often develop Korsakoff's syndrome because most of their caloric intake comes in the form of alcohol, which lacks vitamins, and because alcohol interferes with the metabolism of what little thiamine they do consume. However, alcohol has been shown to accelerate the development of brain damage in thiamine-deficient rats, so it may have a direct toxic effect on the brain as well (Ridley, Draper, & Withall, 2013).

The point of this discussion of Korsakoff's syndrome is to show you that progress in biopsychology typically comes from converging operations—in this case, from the convergence of neuropsychological case studies (case studies of Korsakoff patients), quasiexperiments with human participants (comparisons of heavy drinkers with abstainers), and controlled experiments on laboratory animals (comparison of thiamine-deficient and control rats). The strength of biopsychology lies in the diversity of its methods and approaches. This means that, in evaluating biopsychological claims, it is rarely sufficient to consider the results of one study or even of one line of experiments using the same method or approach.

So what has all the research on Korsakoff's syndrome done for Jimmie G. and others like him? Today, heavy drinkers are counseled to stop drinking and are treated with large doses of thiamine. The thiamine limits the development of further brain damage and often leads to a slight improvement in the patient's condition; unfortunately, the acquired brain dysfunction is mostly irreversible.

Scientific Inference: How Do Biopsychologists Study the Unobservable Workings of the Brain?

LO 1.14 Explain scientific inference with reference to research on eye movements and the visual perception of motion.

Scientific inference is the fundamental method of biopsychology and of most other sciences—it is what makes being a scientist fun. This section provides further insight into the nature of biopsychology by defining, illustrating, and discussing scientific inference.

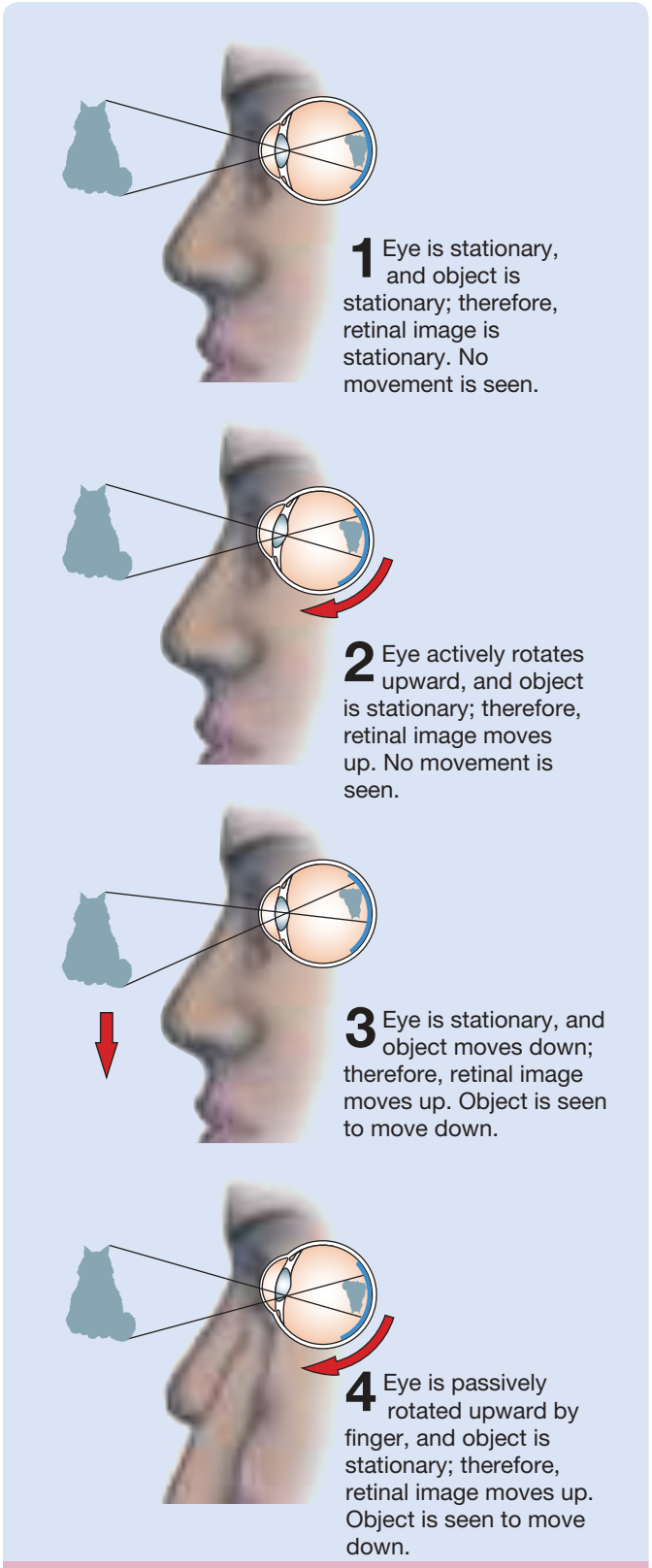
The scientific method is a system for finding things out by careful observation, but many of the processes studied by scientists cannot be observed. For example, scientists use empirical (observational) methods to study ice ages, gravity, evaporation, electricity, and nuclear fission—none of which can be directly observed; their effects can be observed, but the processes themselves cannot. Biopsychology is no different from other sciences in this respect. One of its main goals is to characterize, through empirical methods, the unobservable processes by which the nervous system controls behavior.

The empirical method that biopsychologists and other scientists use to study the unobservable is called **scientific inference**. Scientists carefully measure key events they can observe and then use these measures as a basis for logically inferring the nature of events they cannot observe. Like a detective carefully gathering clues from which to re-create an unwitnessed crime, a biopsychologist carefully gathers relevant measures of behavior and neural activity from which to infer the nature of the neural processes that regulate behavior. The fact that the neural mechanisms of behavior cannot be directly observed and must be studied through scientific inference is what makes biopsychological research such a challenge—and, as we said before, so much fun.

To illustrate scientific inference, we have selected a research project in which you can participate. By making a few simple observations about your own visual abilities under different conditions, you will be able to discover the principle by which your brain translates the movement of images on your retinas into perceptions of movement (see Figure 1.7). One feature of the mechanism is immediately obvious. Hold your hand in front of your face, and then move its image across your retinas by moving your eyes, by moving your hand, or by moving both at once. You will notice that only those movements of the retinal image produced by the movement of your hand are translated into the perception of motion; movements of the retinal image produced by your own eye movements are not. Obviously, there must be a part of your brain that monitors the movements of your retinal image and subtracts from the total those image movements produced by your own eye movements, leaving the remainder to be perceived as motion.

Now, let's try to characterize the nature of the information about your eye movements used by your brain in its perception of motion. Try the following. Shut one eye, then rotate your other eye slightly upward by gently pressing on your lower eyelid with your fingertip. What do you see? You see all of the objects in your visual field moving downward. Why? It seems that the brain mechanism responsible for the perception of motion does not consider eye movement per se. It considers only those eye movements that are actively produced by neural signals from the brain to the eye muscles, not those that are passively produced by

Figure 1.7 The perception of motion under four different conditions.



other means (e.g., by your finger). Thus, when your eye was moved passively, your brain assumed it had remained still and attributed the movement of your retinal image to the movement of objects in your visual field.

It is possible to trick the visual system in the opposite way; instead of the eyes being moved when no active signals have been sent to the eye muscles, the eyes can be held stationary despite the brain's attempts to move them. Because this experiment involves paralyzing the eye muscles, you cannot participate. Hammond, Merton, and Sutton (1956) injected a *paralytic* (movement-inhibiting) substance into the eye muscles of their participant—who was Merton himself. This paralytic substance was the active ingredient of *curare*, a drug with which some Indigenous people of South America coat their blow darts. What do you think Merton saw when he then tried to move his eyes? He saw the stationary visual world moving in the same direction as his attempted eye movements. If a visual object is focused on part of your retina, and it stays focused there despite the fact that you have moved your eyes to the right, it too must have moved to the right. Consequently, when Merton sent signals to his eye muscles to move his eyes to the right, his brain assumed the movement had been carried out, and it perceived stationary objects as moving to the right.

The point of the eye-movement example is that biopsychologists can learn much about the activities of the brain through scientific inference without directly observing them—and so can you. By the way, neuroscientists are still interested in the kind of feedback mechanisms inferred from the demonstrations of Hammond and colleagues, and they have refined our understanding of the mechanisms using modern neural recording techniques (e.g., Joiner et al., 2013; Wurtz et al., 2011).

Thinking Critically about Biopsychological Claims

We have all heard or read that we use only a small portion of our brains, that it is important to eat three meals a day, that intelligence is inherited, that everybody needs at least 8 hours of sleep per night, that there is a gene for schizophrenia, that heroin is a particularly dangerous (hard) drug, and that neurological diseases can now be cured by genetic engineering. These are but a few of the claims about biopsychological phenomena that have been widely disseminated (see Howard-Jones, 2014). You may believe many of these claims. But are they all true? How does one find out? And if they are not true, why do so many people believe them?

We hope that you will learn how to differentiate between flawed claims and exciting new discoveries. This, the final module of the chapter, begins teaching this lesson.

Evaluating Biopsychological Claims

LO 1.15 Define critical thinking and evaluate biopsychological claims.

As you have already learned, one of the major goals of this text is to teach you how to think creatively (to think in productive, unconventional ways) about biopsychological information. Often, the first step in creative thinking is spotting the weaknesses of existing ideas and the evidence on which they are based—the process by which these weaknesses are recognized is called **critical thinking**. The identification of weaknesses in existing beliefs is one of the major stimuli for scientists to adopt creative new approaches.

Journal Prompt 1.4

Do you think that improving your critical thinking abilities will impact your everyday life? Why or why not? (Suggestion: Revisit this journal prompt once you have finished this course!)

The purpose of this final module of the chapter is to develop your own critical thinking abilities by analyzing two claims that played major roles in the history of biopsychology. In both cases, the evidence proved to be grossly flawed. Notice that if you keep your wits about you, you do not have to be an expert to spot the weaknesses.

The first step in judging the validity of any scientific claim is to determine whether the claim and the research on which it is based were published in a reputable scientific journal. The reason is that, in order to be published in a reputable scientific journal, an article must first be reviewed by experts in the field—usually three or four of them—and judged to be of good quality. Indeed, the best scientific journals publish only a small proportion of the manuscripts submitted to them. You should be particularly skeptical of scientific claims that have not gone through this rigorous review process.

The first case that follows deals with an unpublished claim that was largely dispensed through the news media. The second deals with a claim that was initially supported by published research. Because both of these cases are part of the history of biopsychology, we have the advantage of 20/20 hindsight in evaluating their claims.

Case 1: José and the Bull

José Delgado, a particularly charismatic neuroscientist, demonstrated to a group of newspaper reporters a remarkable new procedure for controlling aggression. Delgado strode into a Spanish bullfighting ring carrying only a red cape and a small radio transmitter. With the transmitter, he could activate a battery-powered stimulator that had previously been mounted on the horns of the other inhabitant of the ring. As the raging bull charged, Delgado calmly activated the stimulator and sent a weak electrical current from the stimulator through an electrode that had been implanted in the caudate nucleus (see Chapter 3), a structure deep in the bull's brain. The bull immediately veered from its charge. After a few such interrupted charges, the bull stood tamely as Delgado swaggered about the ring. According to Delgado, this demonstration marked a significant scientific breakthrough—the discovery of a caudate taming center and the fact that stimulation of this structure could eliminate aggressive behavior, even in bulls specially bred for their ferocity.

To those present at this carefully orchestrated event—and to most of the millions who subsequently read about it—Delgado's conclusion was compelling. Surely, if caudate stimulation could stop the charge of a raging bull, the caudate must be a taming center. It was even suggested that caudate stimulation through implanted electrodes might be an effective treatment for human psychopathy. What do you think?

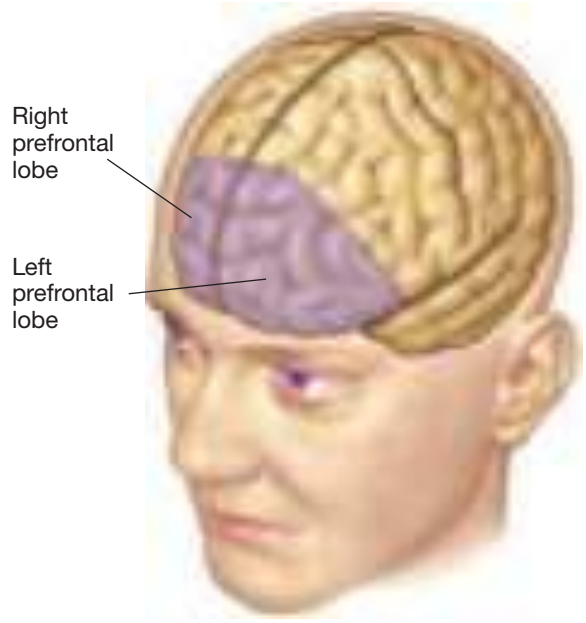
Analysis of Case 1 Delgado's demonstration provided little or no support for his conclusion. It should have been obvious to anyone who did not get caught up in the provocative nature of Delgado's media event that brain stimulation can abort a bull's charge in numerous ways, most of which are simpler, and thus more probable, than the one suggested by Delgado. For example, the stimulation may have simply rendered the bull confused, dizzy, nauseous, sleepy, or temporarily blind rather than nonaggressive; or the stimulation could have been painful. Clearly, any observation that can be interpreted in so many different ways provides little support for any one interpretation. When there are several possible interpretations for a behavioral observation, the rule is to give precedence to the simplest one; this rule is called **Morgan's Canon**. The following comments of Valenstein (1973) provide a reasoned view of Delgado's demonstration:

> Actually there is no good reason for believing that the stimulation had any direct effect on the bull's aggressive tendencies. An examination of the film record makes it apparent that the charging bull was stopped because as long as the stimulation was on it was forced to turn around in the same direction continuously. After examining the film, any scientist with knowledge in this field could conclude only that the stimulation had been activating a neural pathway controlling movement. (p. 98)

Case 2: Two Chimpanzees, Moniz, and the Prefrontal Lobotomy

In 1949, Dr. Egas Moniz was awarded the Nobel Prize in Physiology and Medicine for the development of **prefrontal lobotomy**—a surgical procedure in which the connections between the prefrontal lobes and the rest of the brain are cut as a treatment for mental illness. The **prefrontal lobes** are the large areas, left and right, at the very front of the brain (see Figure 1.8). Moniz's discovery was based on the report that two

Figure 1.8 The right and left prefrontal lobes, whose connections to the rest of the brain are disrupted by prefrontal lobotomy.



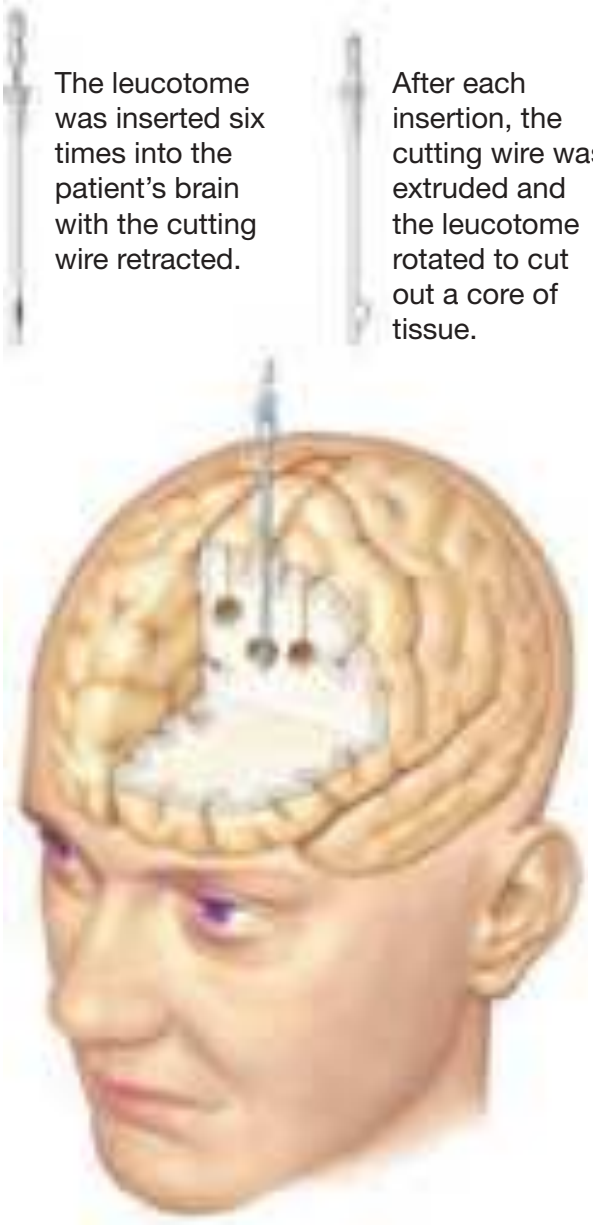
chimpanzees that frequently became upset when they made errors during the performance of a food-rewarded task, did not do so following the creation of a large *bilateral lesion* (an area of damage to both sides of the brain) of their prefrontal lobes. After witnessing a demonstration of this result at a scientific meeting in 1935, Moniz convinced neurosurgeon Almeida Lima to operate on a series of psychiatric patients (see Heller et al., 2006). Lima cut out six large cores of prefrontal tissue with a surgical device called a **leucotome** (see Figure 1.9).

Following Moniz's claims that prefrontal surgery was therapeutically useful, there was a rapid proliferation of various forms of prefrontal psychosurgery. One such variation was **transorbital lobotomy**, which was developed in Italy and then popularized in the United States by Walter Freeman in the late 1940s. It involved inserting an ice pick-like device under the eyelid, driving it through the orbit (the eye socket) with a few taps of a mallet, and pushing it into the prefrontal lobes, where it was waved back and forth to sever the connections between the prefrontal lobes and the rest of the brain (see Figure 1.10). This operation was frequently performed in doctors' offices.

Analysis of Case 2 Incredible as it may seem, Moniz's program of **psychosurgery** (any brain surgery, such as prefrontal lobotomy, performed for the treatment of a psychological problem) was largely based on the observation of two chimpanzees. Thus, Moniz displayed a lack of appreciation for the diversity of brain and behavior, both within and between species. No program of psychosurgery should ever be initiated without a thorough assessment of the effects of the surgery on a large sample of subjects from various nonhuman mammalian species. To do so is not only unwise, it is unethical.

A second major weakness in the scientific case for prefrontal lobotomy was the failure of Moniz and others to carefully

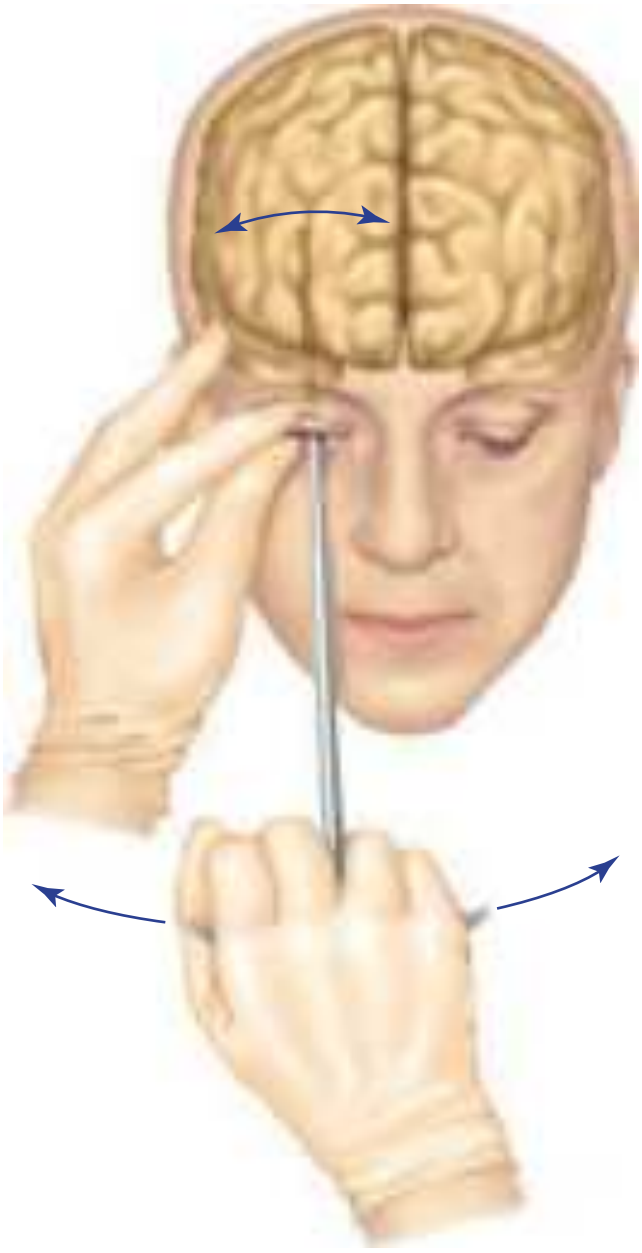
Figure 1.9 The prefrontal lobotomy procedure developed by Moniz and Lima.



evaluate the consequences of the surgery in the first patients to undergo the operation (see Mashour, Walker, & Martuza, 2005; Singh, Hallmayer, & Illes, 2007). The early reports that the operation was therapeutically effective were based on the impressions of the individuals who were the least objective—the physicians who had prescribed the surgery and their colleagues. Patients were frequently judged as improved if they were more manageable, and little effort was made to evaluate more important aspects of their psychological adjustment or to document the existence of adverse side effects.

Eventually, it became clear that prefrontal lobotomies are of little therapeutic benefit and that they can produce a wide range of undesirable side effects, such as socially inappropriate behavior, lack of foresight, emotional unresponsiveness, epilepsy, and urinary incontinence. This led to the abandonment of prefrontal lobotomy in many parts of the world—but not before more

Figure 1.10 The transorbital procedure for performing prefrontal lobotomy.



than 40,000 patients had been lobotomized in the United States alone. And prefrontal lobotomies still continue to be performed in some countries.

A particularly troubling aspect of the use of prefrontal lobotomy is that not only informed, consenting adults received this "treatment." In his memoir, Howard Dully described how he had been lobotomized at the age of 12 (Dully & Fleming, 2007). The lobotomy was arranged by Dully's stepmother, agreed to by his father, and performed in 10 minutes by Walter Freeman. Dully spent most of the rest of his life in asylums, jails, and halfway houses, wondering what he had done to deserve the lobotomy and how much it had been responsible for his troubled life. Subsequent investigation of the case indicated that Dully was a normal child whose stepmother was obsessed by her hatred for him. Tragically, neither his father nor the medical profession intervened to protect him from Freeman's ice pick.

Some regard sound scientific methods as unnecessary obstacles in the paths of patients seeking treatment and therapists striving to provide it. However, the unforeseen consequences of prefrontal lobotomy should caution us against abandoning science for expediency. Only by observing the rules of science can scientists protect the public from bogus claims (see Rousseau & Gunia, 2016).

Thankfully, biopsychology has learned from the mistakes and faulty thinking of Delgado, Moniz, Freeman, and others. The practice of the scientific method and well-reasoned inference are nearly ubiquitous in modern biopsychology.

You are about to enter the amazing world of biopsychology. We hope your brain enjoys learning about itself.

Themes Revisited

The seeds of three of the major themes were planted in this chapter, but the thinking creatively theme predominated. First, you saw the creative approach that Lester and Gorzalka took in their research on the Coolidge effect in females. Then, you learned three important new ideas that will help you think about biopsychological claims: (1) the experimental method, (2) converging operations, and (3) scientific inference. Finally, you were introduced to two biopsychological claims that were once widely believed and saw how critical thinking identified their weaknesses and replaced them with creative new interpretations.

You also learned that two of the other major themes—clinical implications and the evolutionary perspective—tend to be associated with particular divisions of biopsychology. Clinical implications most commonly emerge from neuropsychological, psychopharmacological, and psychophysiological research; the evolutionary perspective is a defining feature of comparative psychology.

The two emerging themes, thinking about epigenetics and consciousness, will appear in later chapters.

Key Terms

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Neuroscience, p. 26
Thinking creatively, p. 27
Clinical, p. 27
Evolutionary perspective, p. 27
Neuroplasticity, p. 28
Epigenetics, p. 28
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Chapter 2

Evolution, Genetics, and Experience

Thinking about the Biology of Behavior

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Chapter Overview and Learning Objectives

Thinking about the Biology of Behavior: From Dichotomies to Interactions	**LO 2.1** Describe the origins of the physiological–psychological and nature–nurture ways of thinking.
	LO 2.2 Explain why thinking about the biology of behavior in terms of traditional physiological–psychological and nature–nurture dichotomies is flawed.
Human Evolution	**LO 2.3** Describe the origins of evolutionary theory.
	LO 2.4 Explain the evolutionary significance of social dominance and courtship displays.
	LO 2.5 Summarize the pathway of evolution from single-cell organisms to humans.
	LO 2.6 Describe nine commonly misunderstood points about evolution.

	LO 2.7 Describe how research on the evolution of the human brain has changed over time.
Fundamental Genetics	**LO 2.8** Explain how Mendel's work with pea plants has informed us about the mechanisms of inheritance.
	LO 2.9 Understand the structure and function of chromosomes.
	LO 2.10 Describe the process of gene expression.
	LO 2.11 Discuss several ways in which modern advances have changed our understanding of genetic processes.
	LO 2.12 Define epigenetics, and explain how it has transformed our understanding of genetics.
Epigenetics of Behavioral Development: Interaction of Genetic Factors and Experience	**LO 2.13** Discuss what insights into the genetics of behavior were gained from early research on selective breeding.
	LO 2.14 Explain how classic research on phenylketonuria (PKU) has informed our understanding of the genetics of behavior.
Genetics of Human Psychological Differences	**LO 2.15** Explain why it is important to distinguish between the development of individuals and the development of individual differences.
	LO 2.16 Explain heritability estimates and how they are commonly misinterpreted.
	LO 2.17 Describe two ways that twin studies can be used to study the interaction of genes and experience (i.e., nature and nurture).

We all tend to think about things in ways that have been ingrained in us by our **zeitgeist** (pronounced "TSYTE-gyste"), the general intellectual climate of our culture. That is why this is a particularly important chapter for you. You see, you are the intellectual product of a zeitgeist that promotes ways of thinking about the biological bases of behavior that are inconsistent with the facts. The primary purpose of this chapter is to help you bring your thinking about the biology of behavior in line with modern biopsychological science.

Thinking about the Biology of Behavior: From Dichotomies to Interactions

We tend to ignore the subtleties, inconsistencies, and complexities of our existence and to think in terms of simple, mutually exclusive dichotomies: right–wrong, good–bad, attractive–unattractive, and so on. The allure of this way of thinking is its simplicity.

The Origins of Dichotomous Thinking

LO 2.1 Describe the origins of the physiological–psychological and nature–nurture ways of thinking.

The tendency to think about behavior in terms of dichotomies is illustrated by two kinds of questions commonly asked about behavior: (1) Is it physiological, or is it psychological? (2) Is it inherited, or is it learned? Both questions have proved to be misguided, yet they are among the most common kinds of questions asked in biopsychology classrooms. That is why we are dwelling on them here.

IS IT PHYSIOLOGICAL, OR IS IT PSYCHOLOGICAL?

The idea that human processes fall into one of two categories, physiological or psychological, has a long history in many cultures. For much of the history of Western cultures, truth was whatever the Church decreed to be true. Then, in about 1400, things started to change. The famines, plagues,

and marauding armies that had repeatedly swept Europe during the Dark Ages subsided, and interest turned to art, commerce, and scholarship—this was the period of the Renaissance, or rebirth (1400–1700). Some Renaissance scholars were not content to follow the dictates of the Church; instead, they started to study things directly by observing them—and so it was that modern science was born.

Much of the scientific knowledge that accumulated during the Renaissance was at odds with Church dictates. However, the conflict was resolved by the prominent French philosopher René Descartes (pronounced "day-CART"). Descartes (1596–1650) advocated a philosophy that, in a sense, gave one part of the universe to science and the other part to the Church. He argued that the universe is composed of two elements: (1) physical matter, which behaves according to the laws of nature and is thus a suitable object of scientific investigation—the human body, including the brain, was assumed to be entirely physical, and so were nonhuman animals; and (2) the human mind (soul, self, or spirit), which lacks physical substance, controls human behavior, obeys no natural laws, and is thus the appropriate purview of the Church.

Cartesian dualism, as Descartes's philosophy became known, was sanctioned by the Roman Church, and so the idea that the human brain and the mind are separate entities became even more widely accepted. It has survived to this day, despite the intervening centuries of scientific progress. Most people now understand that human behavior has a physiological basis, but many still cling to the dualistic assumption that there is a category of human activity that somehow transcends the human brain.

IS IT INHERITED, OR IS IT LEARNED? The tendency to think in terms of dichotomies extends to the way people think about the development of behavioral capacities. For centuries, scholars have debated whether humans and other animals inherit their behavioral capacities or acquire them through learning. This debate is commonly referred to as the **nature–nurture issue**.

Most of the early North American experimental psychologists were totally committed to the nurture (learning) side of the nature–nurture issue. The degree of this commitment is illustrated by the oft-cited words of John B. Watson, the father of *behaviorism*:

> We have no real evidence of the inheritance of [behavioral] traits. I would feel perfectly confident in the ultimately favorable outcome of careful upbringing of a healthy, well-formed baby born of a long line of crooks, murderers and thieves, and prostitutes. Who has any evidence to the contrary?
>
> . . . Give me a dozen healthy infants, well-formed, and my own specified world to bring them up in and I'll guarantee to take any one at random and train him to become any type of specialist I might select—doctor, lawyer, artist, merchant-chief and, yes even beggar-man and thief. (Watson, 1930, pp. 103–104)

At the same time experimental psychology was taking root in North America, **ethology** (the study of animal behavior in the wild) was becoming the dominant approach to the study of behavior in Europe. European ethology, in contrast to North American experimental psychology, focused on the study of **instinctive behaviors** (behaviors that occur in all like members of a species, even when there seems to have been no opportunity for them to have been learned), and it emphasized the role of nature, or inherited factors, in behavioral development. Because instinctive behaviors are not learned, the early ethologists assumed they are entirely inherited. They were wrong, but then so were the early experimental psychologists.

Problems with Thinking about the Biology of Behavior in Terms of Traditional Dichotomies

LO 2.2 Explain why thinking about the biology of behavior in terms of traditional physiological–psychological and nature–nurture dichotomies is flawed.

The physiological-or-psychological debate and the nature-or-nurture debate are based on incorrect ways of thinking about the biology of behavior, and a new generation of questions is directing the current boom in biopsychological research (see Churchland, 2002). What is wrong with these old ways of thinking about the biology of behavior, and what are the new ways?

PHYSIOLOGICAL-OR-PSYCHOLOGICAL THINKING RUNS INTO DIFFICULTY. Not long after Descartes's mind–brain dualism was officially sanctioned by the Roman Church, it started to come under public attack.

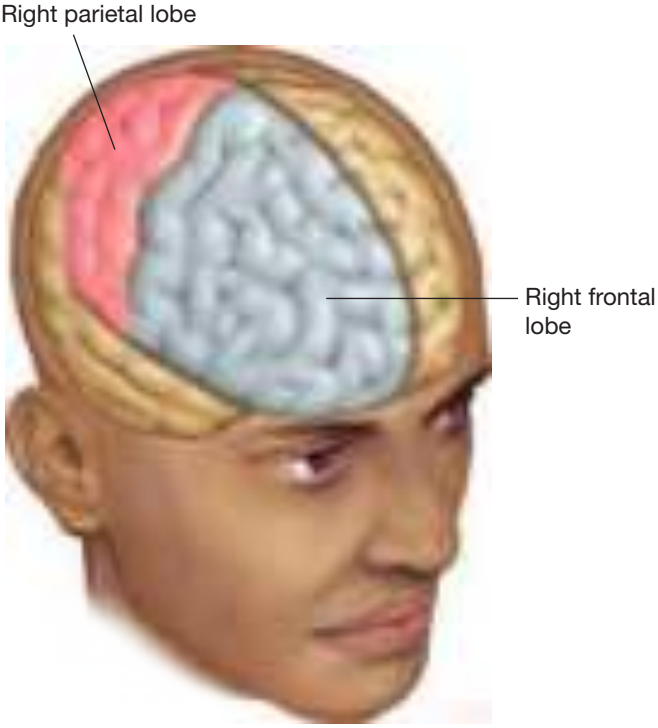
> In 1747, Julien Offray de la Mettrie anonymously published a pamphlet that scandalized Europe. . . . La Mettrie fled to Berlin, where he was forced to live in exile for the rest of his life. His crime? He had argued that thought was produced by the brain—a dangerous assault, in the eyes of his contemporaries. (Corsi, 1991, cover)

There are two lines of evidence against *physiological-or-psychological thinking* (the assumption that some aspects of human psychological functioning are so

complex that they could not possibly be the product of a physical brain). The first line is composed of the many demonstrations that even the most complex psychological changes (e.g., changes in self-awareness, memory, or emotion) can be produced by damage to, or stimulation of, parts of the brain (see Farah & Murphy, 2009). The second line of evidence is composed of demonstrations that some nonhuman species, particularly *primate* species, possess some abilities (e.g., complex problem solving) that were once assumed to be purely psychological and thus purely human (see Bartal, Decety, & Mason, 2011). The following two cases illustrate these two kinds of evidence. Both cases deal with self-awareness, which is widely regarded as one hallmark of the human mind (see Apps & Tsakiris, 2014).

The first case is Oliver Sacks's (1985) account of "the man who fell out of bed." This patient was suffering from **asomatognosia**, a deficiency in the awareness of parts of one's own body. Asomatognosia typically involves the left side of the body and usually results from damage to the *right frontal and parietal lobes* (see Feinberg et al., 2010; Figure 2.1). The point here is that, although the changes in self-awareness displayed by the patient were very complex, they were clearly the result of brain damage: Indeed, the full range of human experience can be produced by manipulations of the brain.

Figure 2.1 Asomatognosia often involves damage to the right frontal and parietal lobes.



The Case of the Man Who Fell Out of Bed

When he awoke, Dr. Sacks's patient felt fine—that is, until he touched the thing in bed next to him. It was a severed human leg, all hairy and still warm! At first, the patient was confused. Then he figured it out. One of the nurses must have taken it from the autopsy department and put it in his bed as a joke. Some joke; it was disgusting. So, he threw the leg out of the bed, but somehow he landed on the floor with it attached to him.

The patient became agitated and desperate, and Dr. Sacks tried to comfort him and help him back into the bed. Making one last effort to reduce the patient's confusion, Sacks asked him where his left leg was, if the one attached to him wasn't it. Turning pale and looking like he was about to pass out, the patient replied that he had no idea where his own leg was—it had disappeared.

The second case describes G. G. Gallup's research on self-awareness in chimpanzees (see Gallup, 1983; Parker, Mitchell, & Boccia, 1994). The point of this case is that even nonhumans, which are assumed by some people to have no mind, are capable of considerable psychological complexity—in this case, self-awareness. Although their brains are less complex than the brains of humans, some species are capable of high levels of psychological complexity (see Gomez-Marin & Mainen, 2016).

The Case of the Chimps with Mirrors*

One way of assessing an organism's self-awareness is to confront it with a mirror. Invariably, the first reaction of a chimpanzee to a mirror is to respond as if it were seeing another chimpanzee. However, after a day or two, it starts to act as if it were self-aware. It starts to use the mirror to groom itself, inspect parts of its body, and experiment with its reflection by making faces and assuming unusual postures while monitoring the results in the mirror.

In an attempt to provide even more convincing evidence of self-awareness, Gallup (1983) devised a clever test. Each chimpanzee was anesthetized, and its eyebrow was painted with a red, odorless, dye. Following recovery from anesthesia, the mirror was reintroduced. Upon seeing its painted eyebrow in the mirror, each chimpanzee repeatedly touched the marked area on its eyebrow while watching the image (see Figure 2.2.) Moreover, there was over a threefold increase in the time that the chimps spent looking in the mirror, and several kept touching their eyebrows and smelling their fingers. We suspect that you would respond pretty much the same way if you saw yourself in the mirror with a red spot on your face.

(*continued*)

* "Toward a Comparative Psychology of Mind" by G. G. Gallup, Jr., *American Journal of Primatology* 2:237–248, 1983. Copyright © 1983 John Wiley & Sons, Inc.

Figure 2.2 The reactions of chimpanzees to their *own* images suggest that they are self-aware. In this photo, the chimpanzee is reacting to the bright red, odorless dye that was painted on its eyebrow ridge while it was anesthetized.

The Povinelli Group LLC

Since Gallup's demonstration, many other species have passed what is now known as the *mirror self-recognition test*. These include Asian elephants, orangutans, and European magpies, to name a few. We humans pass the mirror self-recognition test only once we have reached 15 to 24 months of age.

NATURE-OR-NURTURE THINKING RUNS INTO DIFFICULTY. The history of nature-or-nurture thinking can be summed up by paraphrasing Mark Twain: "Reports of its death have been greatly exaggerated." Each time it has been discredited, it has resurfaced in a slightly modified form. First, factors other than genetics and learning were shown to influence behavioral development; factors such as the fetal environment, nutrition, stress, and sensory stimulation all proved to be influential. This led to a broadening of the concept of nurture to include a variety of experiential factors in addition to learning. In effect, it changed the nature-or-nurture dichotomy from "genetic factors or learning" to "genetic factors or experience."

Next, it was argued convincingly that behavior always develops under the combined control of both nature and nurture (see Johnston, 1987; Rutter, 1997), not under the control of one or the other. Faced with this point, many people merely substituted one kind of nature-or-nurture thinking for another. They stopped asking, "Is it genetic, or is it the result of experience?" and started asking, "How much of it is genetic, and how much of it is the result of experience?"

Like earlier versions of the nature-or-nurture question, the how-much-of-it-is-genetic-and-how-much-of-it-is-the-result-of-experience version is fundamentally flawed. The problem is that it is based on the premise that genetic factors and experiential factors combine in an additive fashion—that a behavioral capacity, such as intelligence, is created by combining some amount of genetics with some amount of experience rather than through the interaction of genetics and experience. Once you learn more about how genetic factors and experience interact, you will better appreciate the folly of this assumption. For the time being, however, let us illustrate its weakness with a metaphor embedded in an anecdote.

The Case of the Thinking Student

One of my students told me (JP) she had read that intelligence was one-third genetic and two-thirds experience, and she wondered whether this was true. I responded by asking her the following question: "If I wanted to get a better understanding of music, would it be reasonable for me to begin by asking how much of it came from the musician and how much of it came from the instrument?"

"That would be dumb," she said. "The music comes from both; it makes no sense to ask how much comes from the musician and how much comes from the instrument. Somehow the music results from the interaction of the two together. You would have to ask about the interaction."

"That's exactly right," I said. "Now, do you see why . . . "

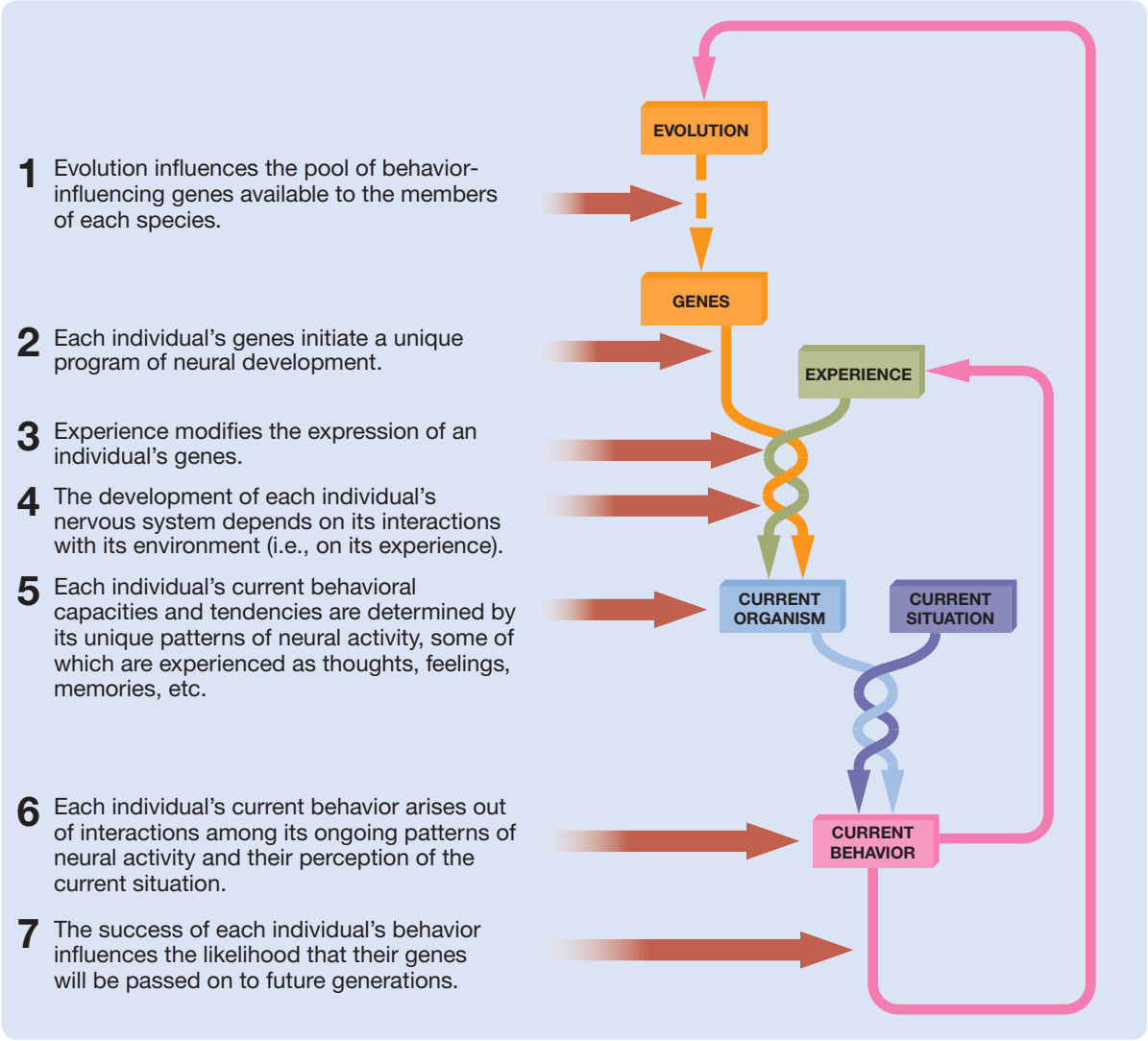
"Don't say any more," she interrupted. "I see what you're getting at. Intelligence is the product of the interaction of genes and experience, and it is dumb to try to find how much comes from genes and how much comes from experience."

"Yes!" I thought.

The point of this metaphor, in case you have forgotten, is to illustrate why it is inappropriate to try to understand interactions between two factors by asking how much each factor contributes. We would not ask how much a musician and how much her instrument contributes to producing music; we would not ask how much the water and how much the temperature contributes to evaporation; and we would not ask how much a male and how much a female contributes to reproduction. Similarly, we shouldn't ask how much genetic and how much experiential factors contribute to behavioral development. The answers to all these questions lie in understanding the nature of the interactions (see Sung et al., 2014; Uher, 2014). The importance of thinking about development in terms of interactions will become even more apparent later in this chapter.

A MODEL OF THE BIOLOGY OF BEHAVIOR. So far in this module, you have learned why people tend to think about the biology of behavior in terms of dichotomies, and you have learned some of the reasons why this way of thinking is inappropriate. Now, let's look at a way of thinking about the biology of behavior that has been adopted by most biopsychologists. It is illustrated in Figure 2.3. Like

Figure 2.3 A schematic illustration of the way in which most biopsychologists think about the biology of behavior.



other powerful ideas, it is simple and logical. This model boils down to the single premise that all behavior is the product of interactions among three factors: (1) the organism's genetic endowment, which is a product of its evolution; (2) its experience; and (3) its perception of the current situation. Please examine the model carefully and consider its implications.

Journal Prompt 2.1

Imagine you are a biopsychology instructor. One of your students asks you whether depression is physiological or psychological. What would you say?

The next three modules of this chapter deal with three elements of this model of behavior: evolution, genetics, and the interaction of genetics and experience in behavioral development. The final module of the chapter deals with the genetics of human psychological differences.

Human Evolution

In this module, you will explore how brain and behavior have been shaped by evolutionary processes. As an entry point to the topic, and to provide some background, you will first learn about the history of the study of evolution. The module then builds upon that foundation by providing you with an overview of several key aspects of the role of evolution in brain and behavior. Moreover, you will learn about some of the most commonly misunderstood aspects about evolution.

Darwin's Theory of Evolution

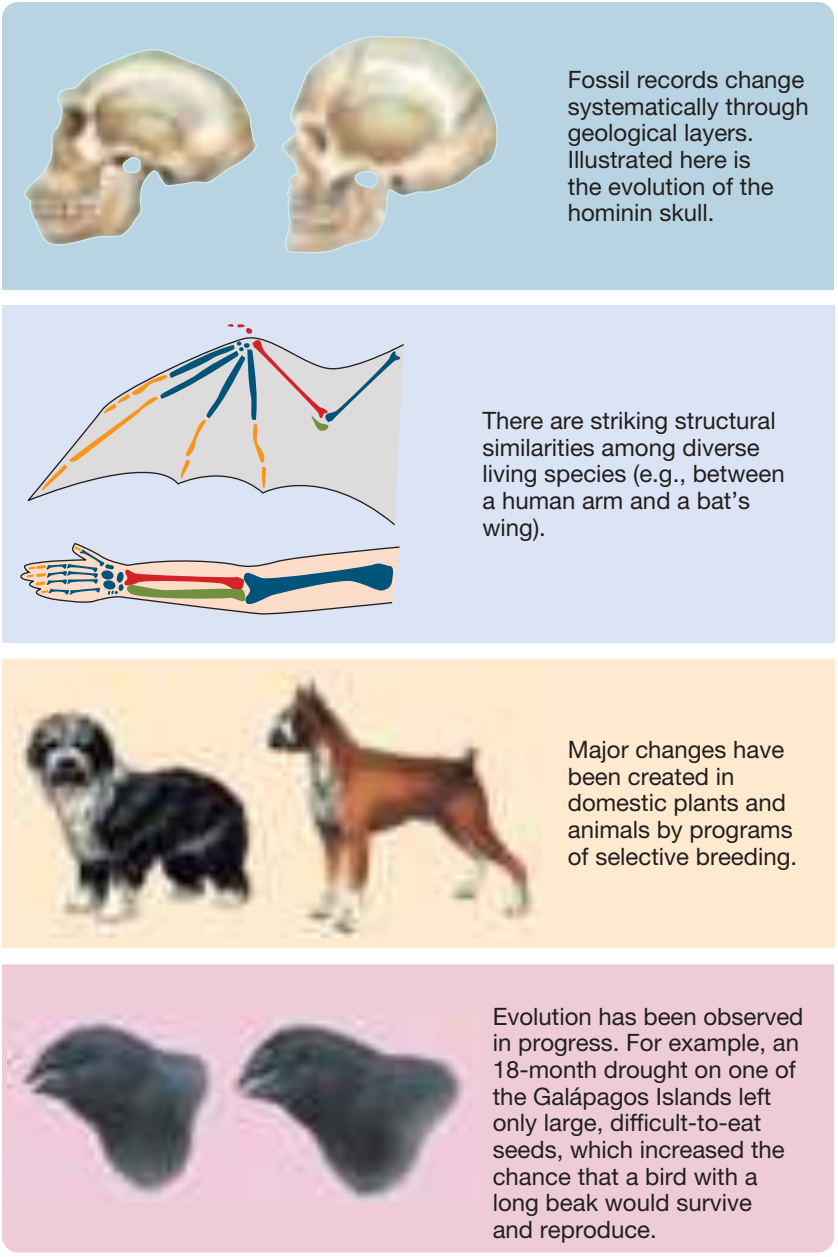
LO 2.3 Describe the origins of evolutionary theory.

Modern biology began in 1859 with the publication of Charles Darwin's *On the Origin of Species*. In this monumental work, Darwin described his theory of evolution—the

single most influential theory in the biological sciences. Darwin was not the first to suggest that species **evolve** (undergo systematic change) from preexisting species, but he was the first to amass a large body of supporting evidence and the first to suggest how evolution occurs (see Bowler, 2009).

Darwin presented three kinds of evidence to support his assertion that species evolve: (1) He documented the evolution of fossil records through progressively more recent geological layers. (2) He described striking structural similarities among living species (e.g., a human's hand, a bird's wing, and a cat's paw), which suggested that they had evolved from common ancestors. (3) He pointed to the major changes that had been brought about in domestic plants and animals by programs of selective breeding. However, the most convincing evidence of evolution comes from direct observations of rapid evolution in progress (see Barrick & Lenski, 2013). For example, Grant (1991) observed evolution of the finches of the Galápagos Islands—a population studied by Darwin himself (see Lamichhaney et al., 2015)—after only a single season of drought. Figure 2.4 illustrates these four kinds of evidence.

Figure 2.4 Four kinds of evidence supporting the theory that species evolve.



Darwin argued that evolution occurs through **natural selection** (see Pritchard, 2010). He pointed out that the members of each species vary greatly in their structure, physiology, and behavior and that the heritable traits associated with high rates of survival and reproduction are the most likely ones to be passed on to future generations (see Kingsley, 2009). He argued that natural selection, when repeated for generation after generation, leads to the evolution of species that are better adapted to surviving and reproducing in their particular environmental niche. Darwin called this process *natural selection* to emphasize its similarity to the artificial selective breeding practices employed by breeders of domestic animals. Just as horse breeders create faster horses by selectively breeding the fastest of their existing stock, nature creates fitter animals by "selectively" breeding the fittest. **Fitness**, in the Darwinian sense, is the ability of an organism to survive and contribute its genes to the next generation.

Darwin's theory of evolution was at odds with the various dogmatic views embedded in the 19th-century zeitgeist, so it initially met with resistance. Although resistance still exists, virtually none comes from people who understand the evidence (see Short & Hawley, 2015).

> Evolution is both a beautiful concept and an important one, more crucial nowadays to human welfare, to medical science, and to our understanding of the world than ever before [see Mindell, 2009]. It's also deeply persuasive—a theory you can take to the bank . . . the supporting evidence is abundant, various, ever increasing, and easily available in museums, popular books, textbooks, and a mountainous accumulation of scientific studies. No one needs to, and no one should, accept evolution merely as a matter of faith. (Quammen, 2004, p. 8)

Evolution and Behavior

LO 2.4 Explain the evolutionary significance of social dominance and courtship displays.

Some behaviors play an obvious role in evolution. For example, the ability to find food, avoid predation, or defend one's young obviously increases an animal's ability to pass on its genes to future generations. Other behaviors play a role that is less obvious but no less important—for example, social dominance and courtship displays, which are discussed here.

SOCIAL DOMINANCE. The males of many species establish a stable *hierarchy of social dominance* through combative encounters with other males (see Qu et al., 2017). In some species, these encounters often involve physical damage; in others, they involve mainly posturing and threatening until one of the two combatants backs down. The dominant male usually wins encounters with all other males of the group; the number two male usually wins encounters with all males except the dominant male; and so on down the line. Once a hierarchy is established, hostilities diminish because the lower-ranking males learn to avoid or quickly submit to the more dominant males. Because most of the fighting goes on between males competing for positions high in the social hierarchy, low-ranking males fight little, and the lower levels of the hierarchy tend to be only vaguely recognizable.

Why is social dominance an important factor in evolution? One reason is that in many species, dominant males copulate more than nondominant males and thus are more effective in passing on their characteristics to future generations. McCann (1981) studied the effect of social dominance on the rate of copulation in 10 bull elephant seals that cohabited the same breeding beach. These massive animals challenge each other by raising themselves to full height and pushing chest to chest. Usually, the smaller of the two backs down; if it does not, a vicious neck-biting battle ensues. McCann found that the dominant male accounted for about 37 percent of the copulations during the study, whereas poor number 10 accounted for only about 1 percent (see Figure 2.5).

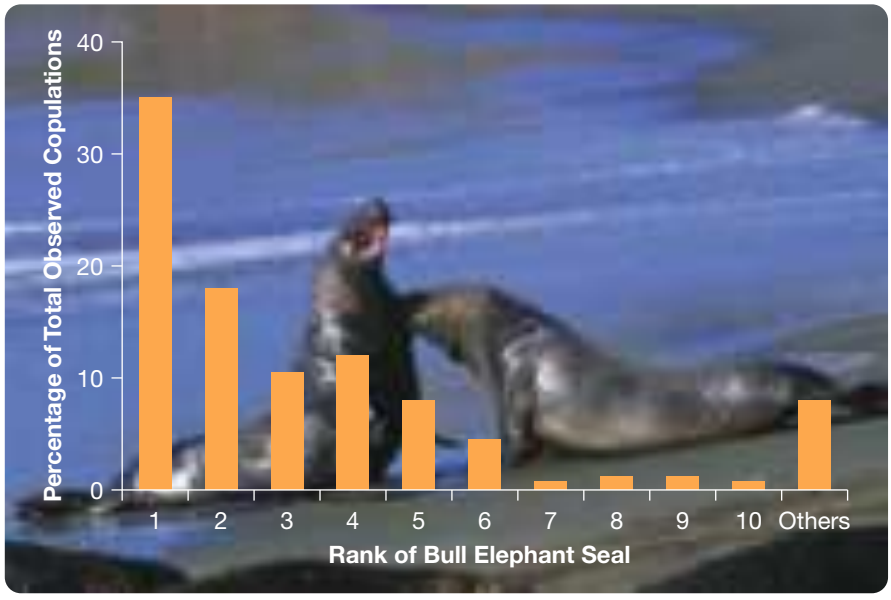
Another reason why social dominance is an important factor in evolution is that in some species, dominant females are more likely to produce more and healthier offspring. For example, Pusey, Williams, and Goodall (1997) found that high-ranking female chimpanzees produced more offspring and that these offspring were more likely to survive to sexual maturity. They attributed these advantages to the fact that high-ranking female chimpanzees are more likely to maintain access to productive foraging areas (see Pusey & Schroepfer-Walker, 2013).

COURTSHIP DISPLAY. An intricate series of courtship displays precedes copulation in many species. The male approaches the female and signals his interest. His signal (which may be olfactory, visual, auditory, or tactual) may elicit a signal in the female, which may elicit another response in the male, and so on, until copulation ensues. But copulation is unlikely to occur if one of the pair fails to react appropriately to the signals of the other.

Courtship displays are thought to promote the evolution of new species. Let us explain. A **species** is a group of organisms reproductively isolated from other organisms; that is, the members of a species can produce fertile offspring only by mating with members of the same species (see de Knijff, 2014). A new species begins to branch off from an existing species when some barrier discourages breeding between a subpopulation of the existing species and the remainder of the species. Once such a reproductive barrier forms, the subpopulation evolves independently of the remainder of the species until cross-fertilization becomes impossible (see Arnegard et al., 2014; Roesti & Salzburger, 2014).

The reproductive barrier may be geographic; for example, a few birds may fly together to an isolated island, where many generations of their offspring breed among themselves and evolve into a separate species. Alternatively—to get back to the main point—the reproductive barrier may be behavioral. A few members of a species may develop

Figure 2.5 Two massive bull elephant seals challenge one another. Dominant bull elephant seals copulate more frequently than those lower in the dominance hierarchy.



Francois Gohier/Science Source

different courtship displays, and these may form a reproductive barrier between themselves and the rest of their **conspecifics** (members of the same species): Only the suitable exchange of displays between a courting couple will lead to reproduction.

Course of Human Evolution

LO 2.5 Summarize the pathway of evolution from single-cell organisms to humans.

By studying fossil records and comparing current species, we humans have looked back in time and pieced together the evolutionary history of our species—although some of the details are still controversial. The course of human evolution, as it is currently understood, is summarized in this section.

EVOLUTION OF VERTEBRATES. Complex multicellular water-dwelling organisms first appeared on earth about 800 million years ago. About 250 million years later, the first chordates evolved (Satoh, 2016). **Chordates** (pronounced "KOR-dates") are animals with dorsal nerve cords (large nerves that run along the center of the back, or *dorsum*); they are 1 of the 40 or so large categories, or *phyla* (pronounced "FY-la"), into which zoologists group animal species (Zhang, 2013). The first chordates with spinal bones to protect their dorsal nerve cords evolved about 25 million years later. The spinal bones are called *vertebrae* (pronounced "VERT-eh-bray"), and the chordates that possess them are called **vertebrates**. The first vertebrates were primitive bony fishes (Shu et al., 1999). Today, there are seven classes of vertebrates: three classes of fishes, plus amphibians, reptiles, birds, and mammals.

EVOLUTION OF AMPHIBIANS. About 410 million years ago, the first bony fishes started to venture out of the water (see Figure 2.6).

Fishes that could survive on land for brief periods of time had two great advantages: They could escape from stagnant pools to nearby fresh water, and they could take advantage of terrestrial food sources. The advantages of life on land were so great that, through the process of natural selection, the fins and gills of bony fishes transformed into legs and lungs, respectively, and so it was that the first **amphibians** evolved about 370 million years ago. Amphibians (e.g., frogs, toads, and salamanders) in their larval form must live in the water; only adult amphibians can survive on land.

EVOLUTION OF REPTILES. About 315 million years ago, reptiles (e.g., lizards, snakes, and turtles) evolved from a branch of amphibians. Reptiles were the first vertebrates to lay shell-covered eggs and to be covered by dry scales. Both of these adaptations reduced the reliance of reptiles on watery habitats. A reptile does not have to spend the first stage of its life in the watery environment of a pond or lake; instead, it spends the first stage of its life in the watery environment of a shell-covered egg. And once hatched, a reptile can live far from water because its dry scales greatly reduce water loss through its water-permeable skin.

EVOLUTION OF MAMMALS. About 225 million years ago, during the height of the age of dinosaurs, a new class of vertebrates evolved from one line of small reptiles. The females of this new class fed their young with secretions from special glands called *mammary glands*, and the members of the class are called **mammals** after these glands. Eventually, mammals stopped laying eggs; instead, the females nurtured their young in the watery environment of their bodies until the young were mature enough to be born. The duck-billed platypus is one surviving mammalian species that lays eggs.

Spending the first stage of life inside one's mother proved to have considerable survival value; it provided the long-term security and environmental stability necessary for complex programs of development to unfold. Today, most classification systems recognize about 26 different orders of mammals. The order to which we belong is the order **primates**. We humans—in our usual humble way—named our order using the Latin term *primus*, which means "first" or "foremost."

Primates have proven particularly difficult to categorize because there is no single characteristic possessed by all primates but no other animals. Still, most experts agree

Figure 2.6 A recently discovered fossil of a missing evolutionary link is shown on the right, and a reconstruction of the creature is shown on the left. It had scales, teeth, and gills like a fish and primitive wrist and finger bones similar to those of land animals.

Beth Rooney Photography

there are about 16 groups of primates. Species from five of them appear in Figure 2.7.

Apes (gibbons, orangutans, gorillas, and chimpanzees) are thought to have evolved from a line of Old World monkeys. Like Old World monkeys, apes have long arms and grasping hind feet that are specialized for arboreal (treetop) travel, and they have opposable thumbs that are not long enough to be of much use for precise manipulation (see Figure 2.8). Unlike Old World monkeys, though, apes have no tails and can walk upright for short distances. Chimpanzees are the closest living relatives of humans; almost 99 percent of genes are identical in the two species (see Rogers & Gibbs, 2014; but see Cohen, 2007); however, the actual ape ancestor of humans is likely long extinct (Jaeger & Marivaux, 2005).

EMERGENCE OF HUMANKIND. Primates of the same group that includes humans are known as **hominins** (see Figure 2.9). Hominins include six sub-groups including *Australopithecus* and *Homo*. Based on the fossil record, *Homo* is thought to be composed of at least eight species (see Wiedemann, 2014; Gibbons, 2015a); seven of which are now extinct. Perhaps you have heard of the Neanderthals (*Homo Neanderthalensis*)? They are one of those extinct *Homo* species. And we humans (*Homo Sapiens)* are the only one still kicking around.

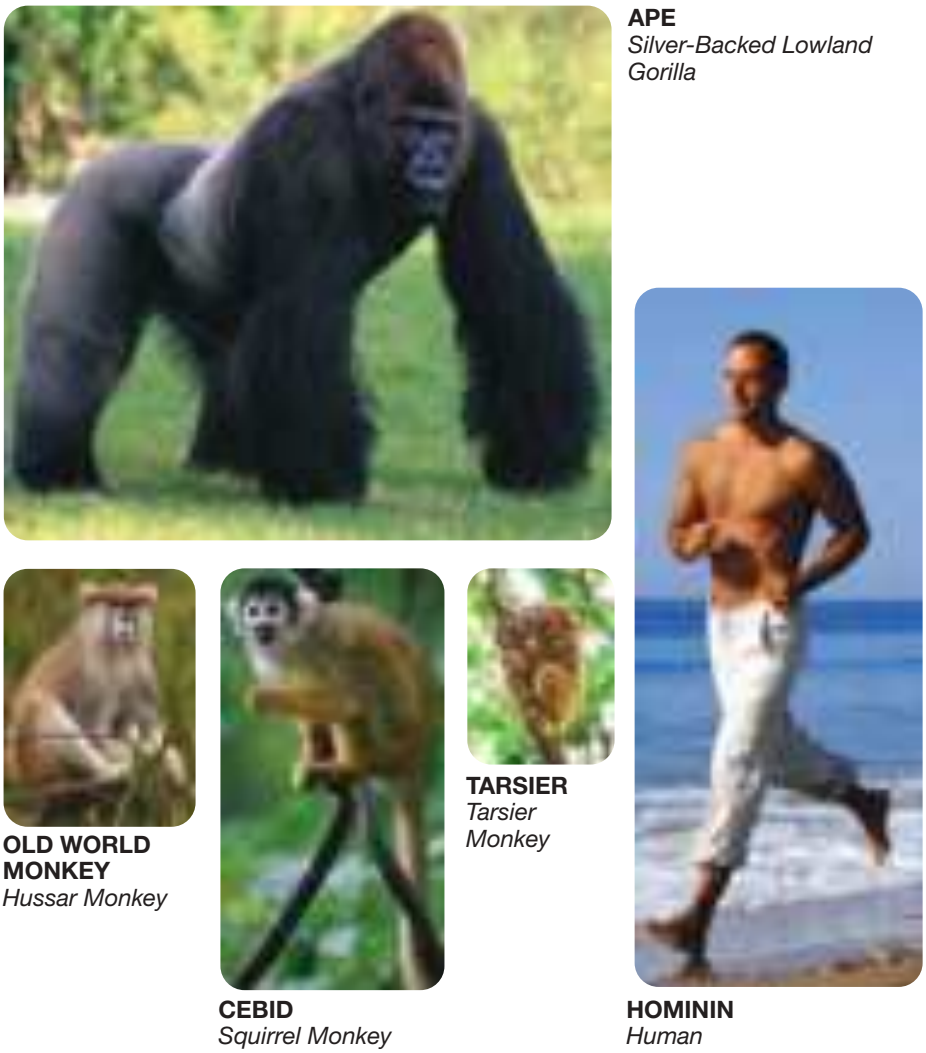
It is difficult to reconstruct the events of human evolution because the evidence is so sparse. Only a few partial hominin fossils dating from the critical period have been discovered. However, three important hominin fossil discoveries have been particularly enlightening (see Harmon, 2013):

- An uncommonly complete fossil of a 3-year-old early *Australopithecus* girl in Ethiopia (see Figure 2.10; Gibbons, 2009; Suwa et al., 2009; White et al., 2009).
- Fossils indicating that a population of tiny hominins inhabited the Indonesian island of Flores as recently as 18,000 years ago (see Callaway, 2014; Stringer, 2014).
- Several early Australopithecine fossils with combinations of human and nonhuman characteristics in a pit in South Africa (Pickering et al., 2011; Wong, 2012).

Many experts believe that the Australopithecines evolved about 4 million years ago in Africa (see Krubitzer & Stolzenberg, 2014; Skinner et al., 2015; Wood, 2010) from a line of apes (*australo* means "southern," and *pithecus* means "ape"). Several species of Australopithecus are thought to have roamed the African plains for about 2 million years before becoming extinct. Australopithecines were only about 1.3 meters (4 feet) tall, and they had small brains, but analysis of their pelvis and leg bones indicates that their posture was upright. Any doubts about their upright posture were erased by the discovery of the fossilized footprints pictured in Figure 2.11 (see Raichlen et al., 2010).

The first *Homo* species are thought to have evolved from one

Figure 2.7 Species from five different groups of primates.



Clockwise from right corner: Kevin Schafer/Photolibrary/Getty Images (APE); Vladimir Sazonov/Shutterstock (HOMININ); Daniel Frauchiger, Switzerland/Moment/Getty Images (TARSIER); Michael Krabs/Alamy Stock Photo (CEBID); Anatoliy Lukich/Shutterstock (OLD WORLD MONKEY)

Figure 2.8 A comparison of the feet and hands of a human and a chimpanzee.

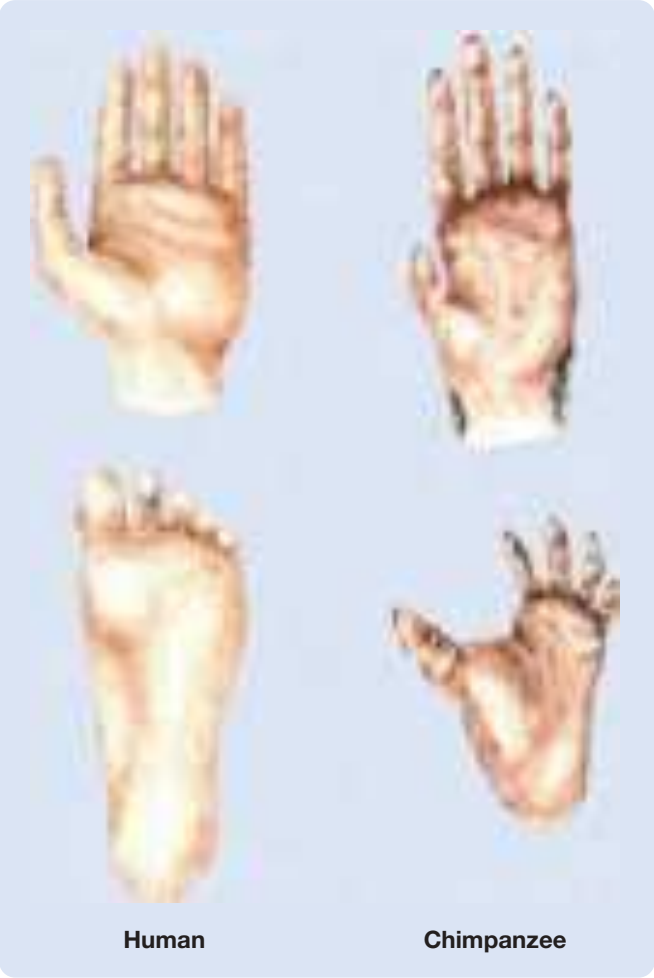


Figure 2.9 A taxonomy of the human species.

Ryan McVay/Getty Images

Figure 2.10 The remarkably complete skull of a 3-year-old *Australopithecus* girl; the fossil is 3.3 million years old.

Lealisa Westerhoff/AFP/Getty Images

species of *Australopithecus* about 2 to 2.8 million years ago (see Antón, Potts, & Aiello, 2014; Dimaggio et al., 2015; Schroeder et al., 2014; Villmoare et al., 2015; but see Wiedemann, 2014; Wood, 2014). One distinctive feature of the early *Homo* species was the size of their brain cavity, larger than that of *Australopithecus* but smaller than that of modern humans. The early *Homo* species used fire and tools (see Orban & Caruana, 2014; Schwartz & Tattersall, 2015) and coexisted in Africa with various species of *Australopithecus* for about a half-million years, until the australopithecines died out. Early *Homo* species also lived outside of Africa for about 1.85 million years (see Lordkipanidze et al., 2013; Wood, 2011). Then, about 275,000 years ago (see Adler et al., 2014), early *Homo* species were gradually replaced in the fossil record by modern humans (*Homo sapiens*).

Paradoxically, although the big three human attributes—large brain, upright posture, and free hands with an opposable thumb—have been evident for hundreds of thousands of years, most human accomplishments are of recent origin. Artistic products (e.g., wall paintings and carvings) did not appear until about 40,000 years ago (see Krubitzer & Stolzenberg, 2014; Pringle, 2013), ranching and farming were not established until about 10,000 years ago (see Larson et al., 2014), and writing was not used until about 7,500 years ago.

Thinking about Human Evolution

LO 2.6 **Describe nine commonly misunderstood points about evolution.**

Figure 2.12 illustrates the main branches of vertebrate evolution. As you examine it, consider the following commonly misunderstood points about evolution. They should

Figure 2.11 Fossilized footprints of Australopithecine hominins who strode across African volcanic ash about 3.6 million years ago, leaving a 70-meter trail. There were two adults and a child; the child often walked in the footsteps of the adults.

John Reader/Science Source

provide you with a new perspective from which to consider your own origins.

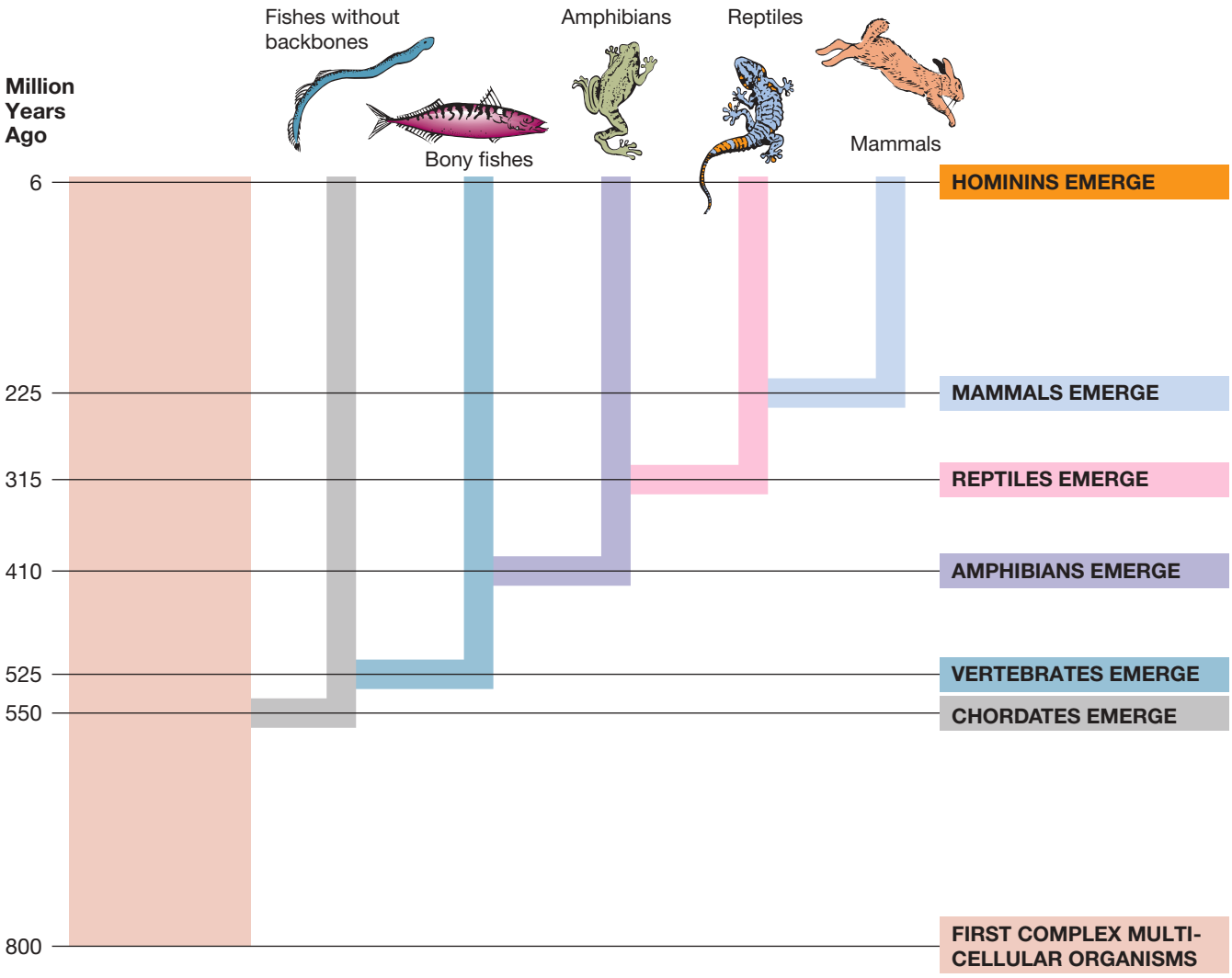
- Evolution does not proceed in a single line. Although it is common to think of an evolutionary ladder or scale, a far better metaphor for evolution is a dense bush.
- We humans have little reason to claim evolutionary supremacy. We are the last surviving species of a group (i.e., *hominins*) that has existed for only a blip of evolutionary time.
- Evolution does not always proceed slowly and gradually. Rapid evolutionary changes (i.e., in a few generations) can be triggered by sudden changes in the environment or by adaptive genetic mutations. Whether human evolution occurred gradually or suddenly is still a matter of intense debate among *paleontologists* (those who scientifically study fossils).
- Few products of evolution have survived to the present day—only the tips of the branches of the evolutionary bush have survived. Fewer than 1 percent of all known species are still in existence.
- Evolution does not progress to preordained perfection—evolution is a tinkerer, not an architect. Increases in adaptation occur through changes to existing programs of development; and, although the results are improvements in their particular environmental context, they are never perfect designs. For example, the fact that mammalian sperm do not develop effectively at body temperature led to the evolution of the scrotum—hardly a perfect solution to any design problem.
- Not all existing behaviors or structures are adaptive. Evolution often occurs through changes in developmental programs that lead to several related characteristics, only one of which might be adaptive—the incidental nonadaptive evolutionary by-products are called **spandrels**. One example of a spandrel is the human belly button—it is a nonfunctional by-product of the umbilical cord. Also, behaviors or structures that were once adaptive might become nonadaptive, or even maladaptive, if the environment changes.

Journal Prompt 2.2

What might be an example of a behavior or structure that is currently adaptive but that might become nonadaptive, or even maladaptive, if our current environment were to change?

- Not all existing adaptive characteristics evolved to perform their current function. Some characteristics, called **exaptations**, evolved to serve one function and were later co-opted to serve another. For example, bird wings are exaptations—they are limbs that initially evolved for the purpose of walking.
- Similarities among species do not necessarily mean that the species have common evolutionary origins. Structures that are similar because they have a common evolutionary origin are termed **homologous**; structures that are similar but do not have a common evolutionary origin are termed **analogous**. The similarities between analogous structures result from **convergent evolution**, the evolution in unrelated species of similar solutions to the same environmental demands (see Stern, 2013). Deciding whether a

Figure 2.12 Hominin evolution.



structural similarity is analogous or homologous requires careful analysis of the similarity. For example, a bird's wing and a human's arm have a basic underlying commonality of skeletal structure that suggests a common ancestor; in contrast, a bird's wing and a bee's wing have few structural similarities, but they both evolved because of the common advantage of flight.

- There is now considerable evidence that *Homo sapiens* mated with other *Homo* species (e.g., Neanderthals) they encountered (see Dannemann & Racimo, 2018; Gibbons, 2014; Wong, 2015). The discovery of this pattern of mating changes the way we should view our origins: We are not the product of a single ancestral *Homo* population; rather, we are the combined offspring of many *Homo* populations that once coexisted and interacted.

Evolution of the Human Brain

LO 2.7 **Describe how research on the evolution of the human brain has changed over time.**

Early research on the evolution of the human brain focused on size. This research was stimulated by the assumption that brain size and intellectual capacity are closely related—an assumption that quickly ran into two problems. First, it was shown that modern humans, whom we humans believe to be the most intelligent of all creatures, do not have the biggest brains. With brains weighing about 1,350 grams, humans rank far behind whales and elephants, whose brains weigh between 5,000 and 8,000 grams (Manger, 2013; Patzke et al., 2014). Second, the sizes of the brains of acclaimed intellectuals (e.g., Albert Einstein) were found to be unremarkable, certainly no match for their gigantic intellects. It is now clear that, although healthy adult

human brains vary greatly in size—between about 1,000 and 2,000 grams—there is no clear relationship between overall human brain size and intelligence.

One obvious problem in relating brain size to intelligence is the fact that larger animals tend to have larger brains, presumably because larger bodies require more brain tissue to control and regulate them. Thus, the facts that large men tend to have larger brains than small men, that men tend to have larger brains than women, and that elephants have larger brains than humans do not suggest anything about the relative intelligence of these populations. This problem led to the proposal that brain weight expressed as a percentage of total body weight might be a better measure of intellectual capacity. This measure allows humans (2.33 percent) to take their rightful place ahead of elephants (0.20 percent), but it also allows both humans and elephants to be surpassed by that intellectual giant of the animal kingdom, the shrew (3.33 percent).

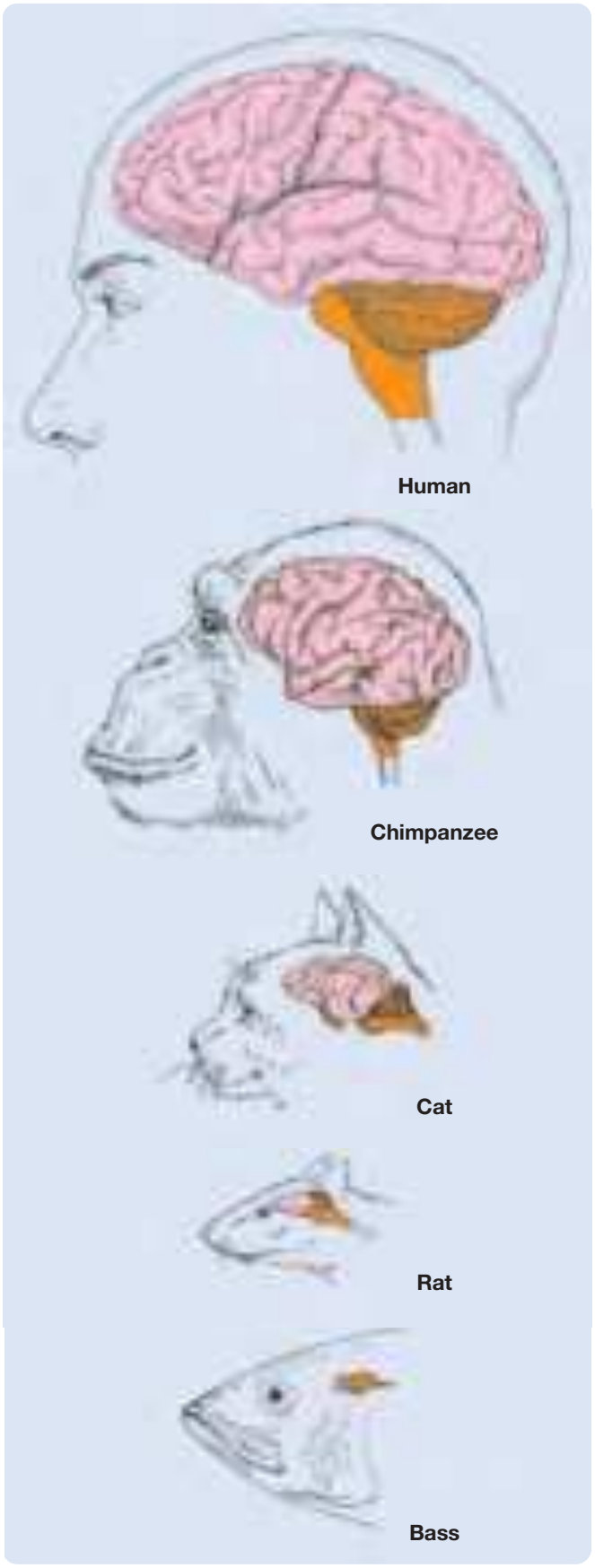
A more reasonable approach to the study of brain evolution has been to compare the evolution of different brain regions. For example, it has been informative to consider the evolution of the **brain stem** separately from the evolution of the **cerebrum** (cerebral hemispheres). In general, the brain stem regulates reflex activities that are critical for survival (e.g., heart rate, respiration, and blood glucose level), whereas the cerebrum is involved in more complex adaptive processes such as learning, perception, and motivation.

Figure 2.13 is a schematic representation of the relative size of the brain stems and cerebrums of several species that are living descendants of species from which humans evolved. This figure makes three important points about the evolution of the human brain:

- The brain has increased in size during evolution.
- Most of the increase in size has occurred in the cerebrum.
- An increase in the number of **convolutions**—folds on the cerebral surface—has greatly increased the surface area of the *cerebral cortex*, the outermost layer of cerebral tissue (see Geschwind & Rakic, 2013; Zilles, Palermo-Gallagher, & Amunts, 2013).

Although the brains of related species differ, there are fundamental similarities: All brains are constructed of many neurons, and the neural structures in the brains of one species can usually be found in the same locations in the brains of related species (see Goulas et al., 2014). For example, the brains of humans, monkeys, rats, and mice contain the same major structures connected in similar ways, and similar structures tend to perform similar functions (see Cole et al., 2009). The human brain appears to have evolved from the brains of our closest primate relatives (see Hofman, 2014; Matsuzawa, 2013).

Figure 2.13 The brains of animals of different evolutionary ages—cerebrums are shown in pink; brain stems are shown in orange.



Scan Your Brain

This is a good place to pause and scan your brain to check your knowledge. Do you remember what you have learned about evolution so far? Fill in the following blanks with the most appropriate terms from the first two modules. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. There has been a long-standing debate on whether humans and other animals inherit their behavioral responses or acquire them through learning. This is called the _____ debate.
2. The condition that can result from damage to the right parietal lobe and typically involves a lack of awareness of one's own body parts (most commonly on the left side) is known as _____.
3. Darwin proposed that the striking similarities among living species were evidence that they shared a common _____.
4. Through selective _____ programs, major changes have been made to domestic animals and plants.
5. In some species, the _____ male is likely to copulate more and, therefore, pass on his genes to the future generations.
6. One distinctive feature of early *Homo* species was that they had brains _____ than Australopithecus but _____ than modern humans.
7. Incidental nonadaptive evolutionary by-products such as the belly button are called _____.
8. During the course of the vertebrate evolution, birds emerged approximately _____ years ago.
9. The overall human brain size does not predict _____.
10. Over millions of years, there has been a remarkable increase in the surface area of the _____, the outmost layer of the cerebral tissue in humans.
11. Evolutionary psychologists suggest that male–female _____ during copulation ensures that the offspring will survive, reproduce, and pass on their genes to the next generation.
12. _____ structures are similar because of convergent evolution.

Scan Your Brain answers: (1) nature–nurture, (2) asomatognosia, (3) ancestor, (4) breeding, (5) dominant, (6) larger, smaller, (7) spandrels, (8) 160 million, (9) intelligence, (10) cerebral cortex, (11) bonding, (12) Analogous.

Fundamental Genetics

Darwin did not understand two of the key facts on which his theory of evolution was based. He did not understand why conspecifics differ from one another, and he did not understand how anatomical, physiological, and behavioral characteristics are passed from parent to offspring. While Darwin puzzled over these questions, an unread manuscript in his files contained the answers. It had been sent to him by an unknown Augustinian monk, Gregor Mendel. Unfortunately for Darwin (1809–1882) and for Mendel (1822–1884), the significance of Mendel's research was not recognized until the early part of the 20th century, well after both of their deaths.

Mendelian Genetics

LO 2.8 Explain how Mendel's work with pea plants has informed us about the mechanisms of inheritance.

Mendel studied inheritance in pea plants. In designing his experiments, he made two wise decisions. He decided to study dichotomous traits, and he decided to begin his experiments by crossing the offspring of true-breeding lines. **Dichotomous traits** occur in one form or the other, never in combination. For example, seed color is a dichotomous pea plant trait: Every pea plant has either brown seeds or white seeds. **True-breeding lines** are breeding lines in which interbred members always produce offspring with the same trait (e.g., brown seeds), generation after generation.

In one of his early experiments, Mendel studied the inheritance of seed color: brown or white. He began by crossbreeding the offspring of a line of pea plants that had bred true for brown seeds with the offspring of a line of pea plants that had bred true for white seeds. The offspring of this cross all had brown seeds. Then, Mendel bred these first-generation offspring with one another, and he found that about three-quarters of the resulting second-generation offspring had brown seeds and about one-quarter had white seeds. Mendel repeated this experiment many times with various pairs of dichotomous pea plant traits, and each time the result was the same: One trait, which Mendel called the **dominant trait**, appeared in all of the first-generation offspring; the other trait, which he called the **recessive trait**, appeared in about one-quarter of the second-generation offspring. Mendel would have obtained a similar result if he had conducted an experiment with true-breeding lines of brown-eyed (dominant) and blue-eyed (recessive) humans.

The results of Mendel's experiment challenged the central premise on which all previous ideas about inheritance had rested: that offspring inherit the traits of their parents. Somehow, the recessive trait (white seeds) was passed on to one-quarter of the second-generation pea plants by first-generation pea plants that did not themselves possess it. An organism's observable traits are referred to as its **phenotype**; the traits that it can pass on to its offspring through its genetic material are referred to as its **genotype**.

Mendel devised a theory to explain his results. It comprised four central ideas. First, Mendel proposed that there are two kinds of inherited factors for each dichotomous trait—for example, that a brown-seed factor and a white-seed factor control seed color. Today, we call each inherited factor a **gene**. Second, Mendel proposed that each organism possesses two genes for each of its dichotomous traits; for example, each pea plant possesses either two brown-seed genes, two white-seed genes, or one of each. The two genes that control the same trait are called **alleles** (pronounced "a-LEELZ"). Organisms that possess two identical alleles (e.g., two white-seed alleles) are said to be **homozygous** for that trait; those that possess different alleles (e.g., one white-seed allele and one black-seed allele) for a trait are said to be **heterozygous** for that trait.

Third, Mendel proposed that one of the two kinds of genes for each dichotomous trait dominates the other in heterozygous organisms. For example, pea plants with a brown-seed gene and a white-seed gene always have brown seeds because the brown-seed gene always dominates the white-seed gene. And fourth, Mendel proposed that for each dichotomous trait, each organism randomly inherits one of its "father's" two factors and one of its "mother's" two factors. Figure 2.14 illustrates how Mendel's theory accounts for the result of his experiment on the inheritance of seed color in pea plants.

Chromosomes

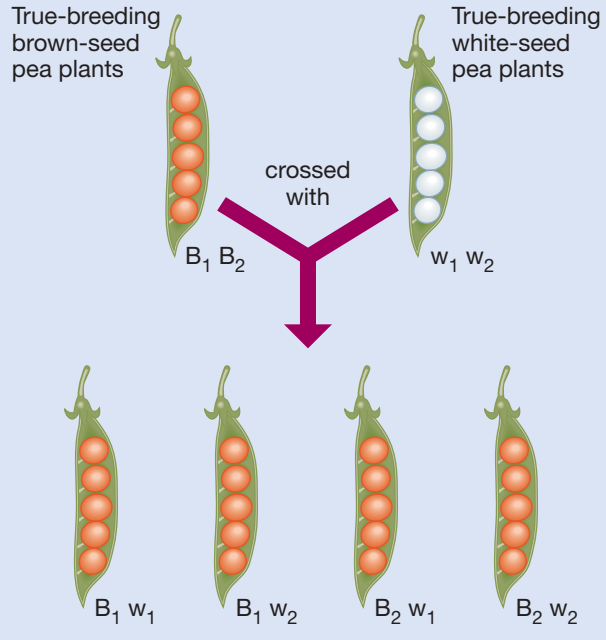
LO 2.9 **Understand the structure and function of chromosomes.**

In this section, you will be presented with current knowledge related to two key aspects of chromosomal function: recombination and replication. The section ends with a discussion of the sex chromosomes and sex-linked traits.

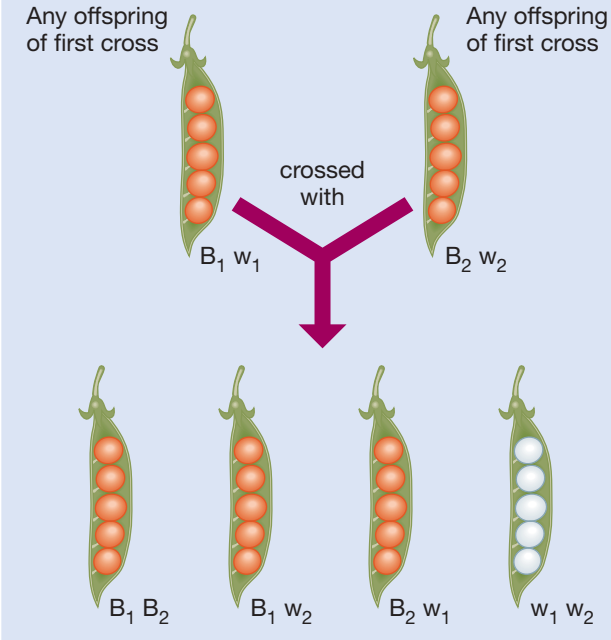
REPRODUCTION AND RECOMBINATION. It was not until the early 20th century that genes were found to be located on **chromosomes**—the threadlike structures in the nucleus of each cell (see Brenner, 2012). Chromosomes occur in matched pairs in virtually all multicellular organisms (see Sagi & Benvenisty, 2017), and each species has a characteristic number of pairs in each of its body cells (but see Sagi & Benvenisty, 2017); humans have 23 pairs. The two genes (alleles) that control each trait are situated at the same location, one on each chromosome of a particular pair.

The process of cell division that produces **gametes** (egg cells and sperm cells) is called **meiosis** (pronounced

Figure 2.14 How Mendel's theory accounts for the results of his experiment on the inheritance of seed color in pea plants.



FIRST CROSS
One parent had two dominant brown-seed genes (B_1 B_2); the other had two recessive white-seed genes (w_1 w_2). Therefore, all offspring had one brown-seed gene and one white-seed gene (B_1 w_1, B_1 w_2, B_2 w_1, or B_2 w_2). Because the brown-seed gene is dominant, all had brown seeds.



SECOND CROSS
Each parent had one brown-seed gene and one white-seed gene. Therefore, 25% of the offspring had two brown-seed genes (B1 B2), 50% had a brown-seed gene and a white-seed gene (B_1 w_2 or B_2 w_1), and 25% had two white-seed genes (w_1 w_2). Because the brown-seed gene is dominant, 75% had brown seeds.

"my-OH-sis"). In meiosis, the chromosomes divide, and one chromosome of each pair goes to each of the two gametes that result from the cell division. As a result, each gamete has only half the usual number of chromosomes (23 in humans); and when a sperm cell and an egg cell combine during fertilization (see Figure 2.15), a **zygote** (a fertilized egg cell) with the full complement of chromosomes (23 pairs in humans) is produced.

The random division of the pairs of chromosomes into two gametes is not the only way meiosis contributes to genetic diversity. Let us explain. During the first stage of meiosis, the chromosomes line up in their pairs. Then, the members of each pair cross over one another at random points, break apart at the points of contact, and exchange sections. As a result of this **genetic recombination**, each of the gametes that formed the zygote that developed into you contained chromosomes that were unique, spliced-together recombinations of chromosomes from your parents.

In contrast to the meiotic creation of the gametes, all other cell division in the body occurs by **mitosis** (pronounced "my-TOE-sis"). Just prior to mitotic division, the number of chromosomes doubles so that, when the cell divides, both daughter cells end up with the full complement of chromosomes (23 pairs in humans).

STRUCTURE AND REPLICATION. Each chromosome is a double-stranded molecule of **deoxyribonucleic acid (DNA)**. Each strand is a sequence of **nucleotide bases** attached to a chain of *phosphate* and *deoxyribose*; there are four nucleotide bases: *adenine*, *thymine*, *guanine*, and *cytosine*. It is the sequence of these bases on each chromosome that constitutes the genetic code—just as sequences of letters constitute the code of our language.

The two strands that compose each chromosome are coiled around each other and bonded together by the attraction of adenine for thymine and guanine for cytosine.

Figure 2.15 During fertilization, sperm cells attach themselves to the surface of an egg cell; at least one must enter the egg cell to fertilize it.

David M. Phillips/Science Source

This specific bonding pattern has an important consequence: The two strands that compose each chromosome are exact complements of each other. For example, a sequence of adenine, guanine, thymine, cytosine, and guanine on one strand is always attached to a complementary sequence of thymine, cytosine, adenine, guanine, and cytosine on the other. Figure 2.16 illustrates the structure of DNA.

Replication is a critical process of the DNA molecule. Without it, mitotic cell division would not be possible. Figure 2.17 illustrates how *DNA replication* is thought to work. The two strands of DNA start to unwind. Then, the exposed nucleotide bases on each of the two strands attract their complementary bases, which are floating in the fluid

Figure 2.16 A schematic illustration of the structure of a DNA molecule. Notice the complementary pairings of nucleotide bases: thymine with adenine and guanine with cytosine.

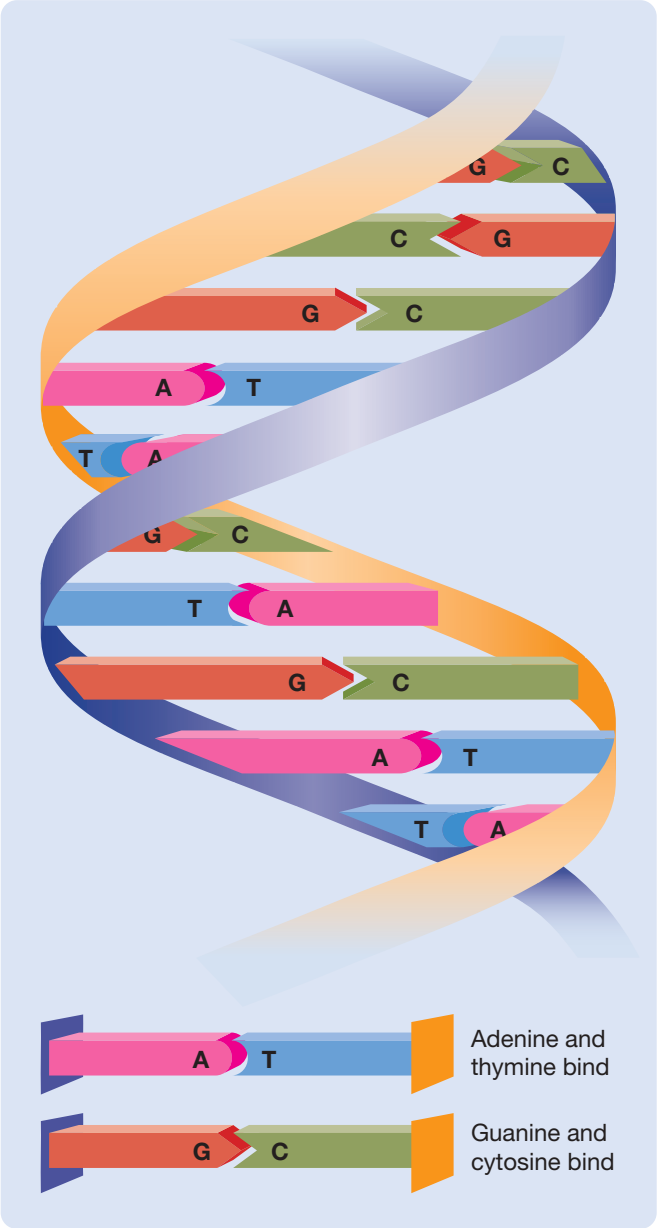


Figure 2.17 DNA replication. As the two strands of the original DNA molecule unwind, the nucleotide bases on each strand attract free-floating complementary bases. Once the unwinding is complete, two DNA molecules, each identical to the first, will have been created.

of the nucleus. Thus, when the unwinding is complete, two double-stranded DNA molecules, both of which are identical to the original, have been created.

Chromosome replication does not always go according to plan; there may be errors. Sometimes, these errors can have significant clinical consequences. For example, in *Down syndrome*, which you will learn about in Chapter 10, there is an extra chromosome in each cell. But more commonly, errors in replication take the form of **mutations**—alterations of individual genes. In most cases, mutations disappear from the gene pool within a few generations because the organisms that inherit them are less fit. However, in some instances, mutations increase fitness and in so doing encourage rapid evolution.

SEX CHROMOSOMES AND SEX-LINKED TRAITS. There is one exception to the rule that chromosomes always come in matched pairs. The typical chromosomes, which come in matched pairs, are called **autosomal chromosomes**; the one exception is the pair of **sex chromosomes**—the pair of chromosomes that determines an individual's sex. There are two types of sex chromosomes, X and Y, and the two look different and carry different genes. Females have two X chromosomes, and males have one X chromosome and one Y chromosome. Traits influenced by genes on the sex chromosomes are referred to as **sex-linked traits**. Virtually all sex-linked traits are controlled by genes on the X chromosome because the Y chromosome is small and carries few genes (see Maekawa et al., 2014).

Traits controlled by genes on the X chromosome occur more frequently in one sex than the other. If the trait is dominant, it occurs more frequently in females. Females have twice the chance of inheriting the dominant gene because they have twice the number of X chromosomes. In contrast, recessive sex-linked traits occur more frequently in males. The reason is that recessive sex-linked traits are manifested only in females who possess two of the recessive genes—one on each of their X chromosomes—whereas the traits are manifested in all males who possess the gene because they have only one X chromosome. The classic example of a recessive sex-linked trait is color blindness. Because the color-blindness gene is quite rare, females almost never inherit two of them and thus almost never possess the disorder; in contrast, every male who possesses one color-blindness gene is color blind.

Genetic Code and Gene Expression

LO 2.10 Describe the process of gene expression.

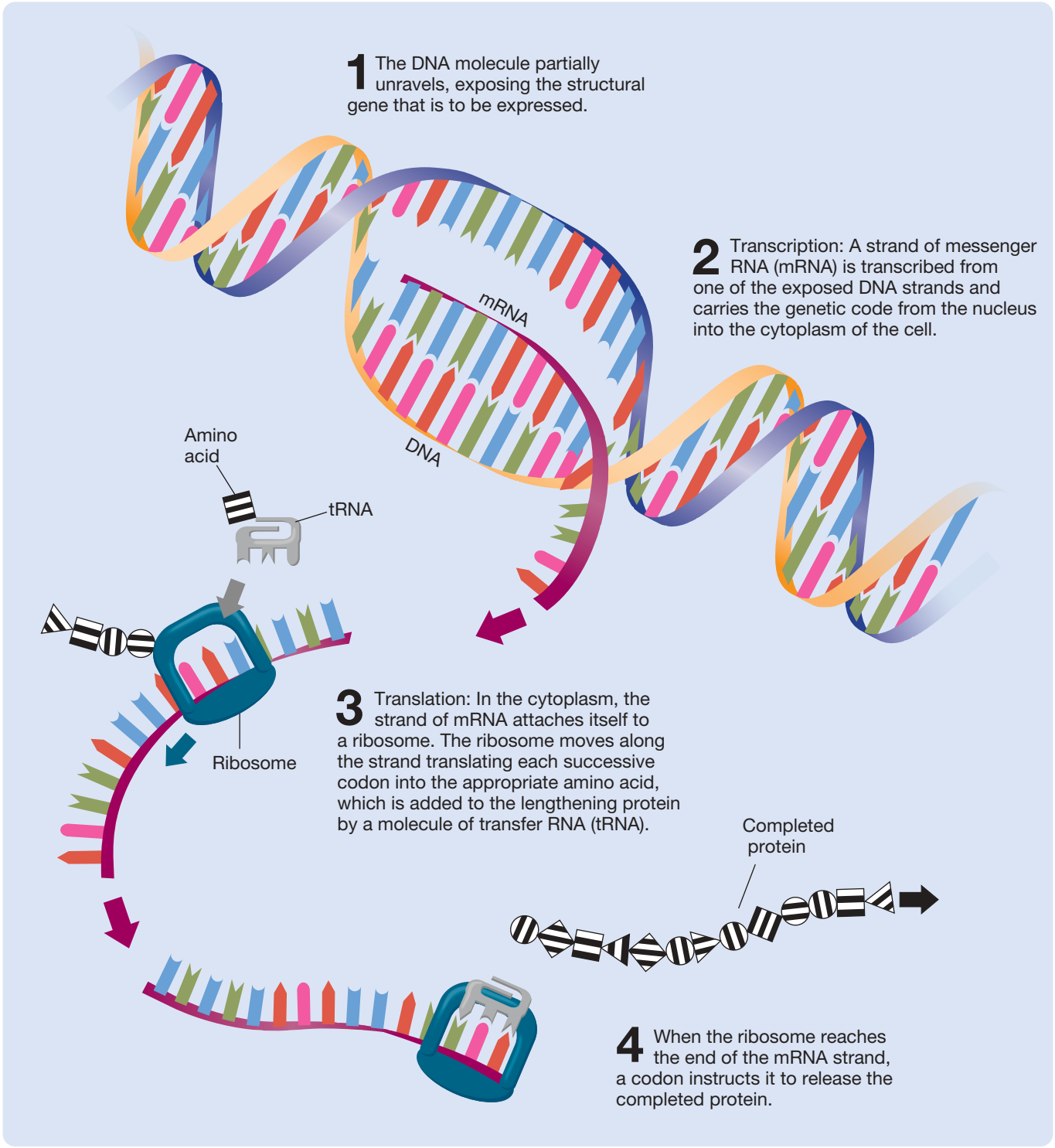
Structural genes contain the information necessary for the synthesis of proteins. **Proteins** are long chains of **amino acids**; they control the physiological activities of cells and are important components of cellular structure. All the cells in the body (e.g., brain cells, hair cells, and bone cells) contain exactly the same genes. How then do different kinds of cells develop? Part of the answer lies in those stretches of DNA that lack structural genes—indeed, although all genes were once assumed to be structural genes, those genes comprise only a small portion of each chromosome.

Although the stretches of DNA that lack structural genes are not well understood, it is clear that they include portions that do serve a function (see Hawkins, Al-attar, & Storey, 2018). These portions, called **promoters**, are stretches of DNA whose function is to determine whether or

not particular structural genes are converted into proteins through a two-phase process known as **gene expression**. The control of gene expression by promoters is an important process because it heavily influences how a cell will develop and how it will function once it reaches maturity. Promoters are like switches because they can be regulated in two ways: They can be turned up, or they can be turned down. Those proteins that bind to DNA and increase gene expression are called **activators**; whereas those that bind to DNA and decrease gene expression are called **repressors**.

The expression of a structural gene is illustrated in Figure 2.18. Gene expression involves two phases. In the first phase, known as **transcription**, the small section of the chromosome that contains the gene unravels, and

Figure 2.18 Gene expression. Transcription of a section of DNA into a complementary strand of messenger RNA (mRNA) is followed by the translation of the messenger RNA strand into a protein.



the unraveled section of one of the DNA strands serves as a template for the transcription of a short strand of **ribonucleic acid (RNA)**. RNA is like DNA except that it contains the nucleotide base uracil instead of thymine and has a phosphate and ribose backbone instead of a phosphate and deoxyribose backbone. The strand of transcribed RNA is called **messenger RNA** because it carries the genetic code out of the nucleus of the cell.

Once the messenger RNA leaves the nucleus, the second phase of gene expression, known as **translation**, begins. During translation, the messenger RNA attaches itself to any one of the many **ribosomes** present in the cell's *cytoplasm* (the clear fluid within the cell). The ribosome then moves along the strand of messenger RNA, translating the genetic code as it proceeds.

Each group of three consecutive nucleotide bases along the messenger RNA strand is called a **codon**. Each codon instructs the ribosome to add 1 of the 20 different kinds of amino acids to the protein it is constructing; for example, the sequence guanine-guanine-adenine instructs the ribosome to add the amino acid glycine. Each kind of amino acid is carried to the ribosome by molecules of **transfer RNA**; as the ribosome reads a codon, it attracts a transfer RNA molecule that is attached to the appropriate amino acid. The ribosome reads codon after codon and adds amino acid after amino acid until it reaches a codon that tells it the protein is complete, whereupon the completed protein is released into the cytoplasm.

In summary, the process of gene expression involves two phases. The first phase involves the transcription of the DNA base-sequence code to an RNA base-sequence code. The second phase involves the translation of the RNA base-sequence code into a protein.

Human Genome Project

LO 2.11 Discuss several ways in which modern advances have changed our understanding of genetic processes.

One of the most ambitious scientific projects of all time began in 1990. Known as the **Human Genome Project**, it was a loosely knit collaboration of major research institutions and individual research teams in several countries. Its purpose was to compile a map of the sequence of all 3 billion nucleotide bases that compose human chromosomes.

The Human Genome Project was motivated by potential medical applications. It was assumed that once the human genome was described, it would be a relatively straightforward matter to link variations in the genome to particular human diseases and then develop treatment and prevention programs tailored to individual patients.

However, more than two decades after the human genome was first described, these medical miracles have yet to be realized (see Hall, 2010). Be that as it may, The Human Genome Project has changed our understanding of ourselves and revolutionized the field of genetics. The following are three major contributions of the Human Genome Project:

- Many new techniques for studying DNA were developed during the Human Genome Project. Many things that were impossible before the Human Genome Project are now routine, and things that took months to accomplish before the Human Genome Project are now possible in only a few hours. Using this new technology, genomes have already been established for many species, including those of many long-extinct species (see Shapiro & Hofreiter, 2014), leading to important insights into evolution.
- The discovery that we humans, the most complex of all species, have relatively few structural genes surprised many scholars. Humans have about 21,000 structural genes; mice have about the same number, and corn has many more. Indeed, protein-encoding genes constitute only about 1 percent of human DNA. Researchers have now generated a nearly complete map of the entire set of proteins encoded for by our genes: the **human proteome** (see Ommen et al., 2018).
- Many variations in the human genome related to particular diseases have been identified. However, this has proven to be less useful than anticipated: So many genes have been linked to each disease that it has proven difficult to sort out the interactions among the numerous genes and experience (Hall, 2010). Compounding the problem is that even when many genes have been linked to a disease, all of them together often account for only a small portion of its heritability (Manolio et al., 2009). For example, 18 different gene variants have been linked to adult-onset diabetes, but these 18 variants account for only 6 percent of the heritability of the disease (see Stumvoll, Goldstein, & van Haeften, 2005).

Modern Genetics: Growth of Epigenetics

LO 2.12 Define epigenetics, and explain how it has transformed our understanding of genetics.

Since the discovery of genes in the 1960s, the structure and expression of protein-encoding genes had been the focus of genetics research and thinking (see Franklin & Mansuy, 2010; Zhang & Meaney, 2010). However, around the turn of the century, the field of genetics changed. Interest shifted away from genes and their expression to other possible mechanisms of inheritance. In particular, interest shifted to the mechanisms by which experience exerts its effects on development. This led to an explosion of interest in an area

of genetics research that had been lingering in the background since 1942: epigenetics. **Epigenetics** is the study of all mechanisms of inheritance other than those mediated by changes to the gene sequence of DNA.

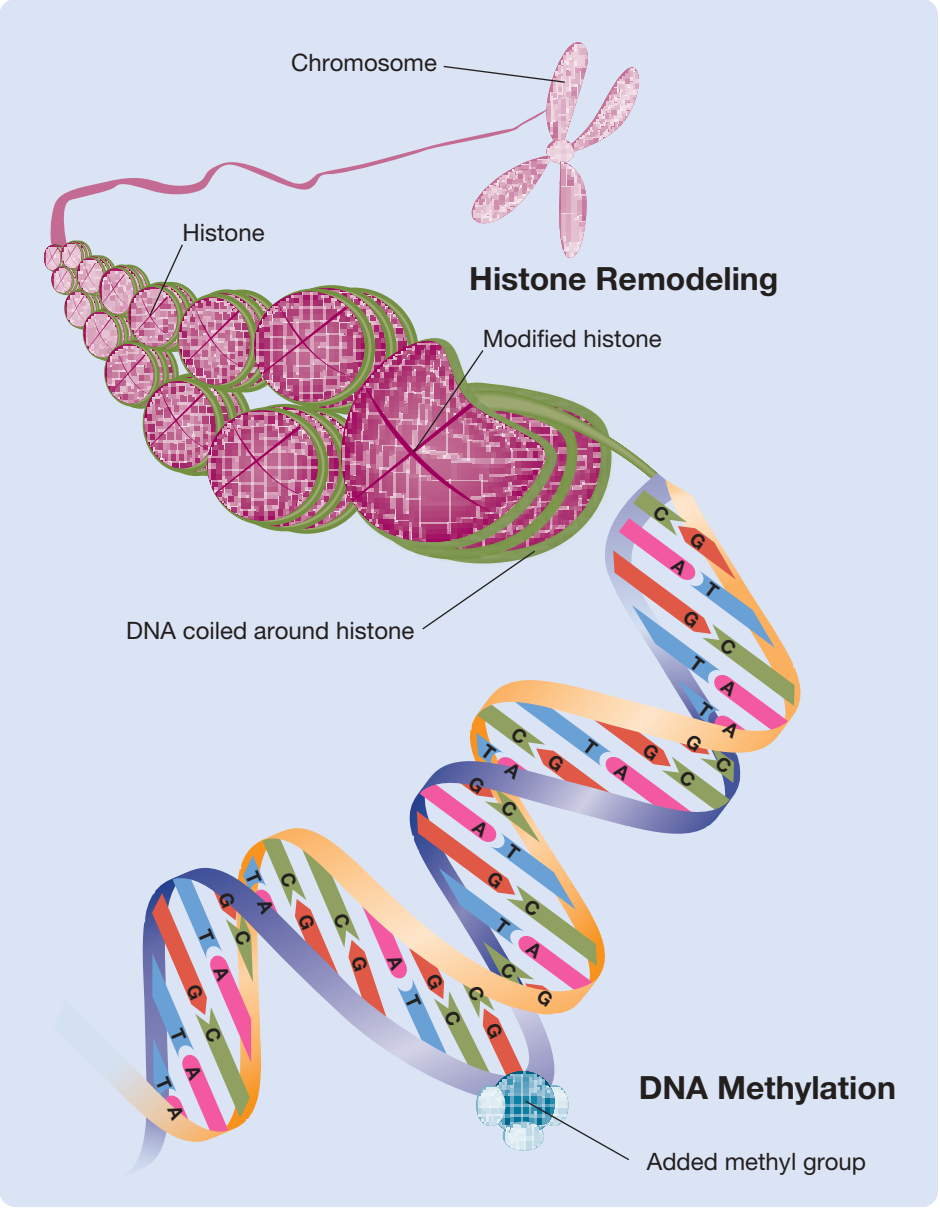
Why did epigenetics rise to prominence so quickly at the turn of the century? Four conditions set the stage. First, the Human Genome Project had generated an arsenal of new research techniques. Second, it was discovered that protein-coding genes constitute only about 1 percent of human DNA—it wasn't clear to researchers what the other 99% was doing (it was widely regarded as "junk DNA"). Third, it was found that the vast majority of RNA molecules were small—only 1.2 percent were of the large protein-encoding variety. This suggested that protein encoding is only a minor function of RNA (see Dolgin, 2015; Wilusz & Sharp, 2013). Finally, although there was a general consensus that development was the product of gene-experience interactions (see Figure 2.3), the mechanisms by which these critical interactions took place were unknown (see Qureshi & Mehler, 2012).

Stimulated by these four conditions, it was not long before a wave of research into epigenetics began to produce important discoveries. Genetics had just spent half a century focused exclusively on the genetic code as the mechanism of inheritance, and the new epigenetic research led to discoveries that challenged this narrow view.

Despite its relative youth, epigenetic research has already amassed an impressive array of discoveries. Here are five important ones:

- Epigenetic investigations of nongene DNA have identified many active areas. Many of these active areas seem to control the expression of nearby genes. Clearly, the belief that nongene DNA is junk DNA is no longer tenable (see Pennisi, 2014; Tragante, Moore, & Asselbergs, 2014).
- Many epigenetic mechanisms that can modulate gene expression have been discovered. Two of the most widely studied are DNA methylation and histone remodeling (see Campbell & Wood, 2019; Cavalli & Heard, 2019; Schultz et al., 2015)—see Figure 2.19. **DNA methylation** is the reaction that occurs when a methyl group attaches to a DNA molecule, usually at cytosine sites in mammals (see Schübeler, 2012). **Histone remodeling** is the reaction that occurs when **histones** (proteins around which DNA is coiled) change their shape and in so doing influence the shape of the adjacent DNA—there are several different mechanisms by which this can occur. Both DNA methylation and histone remodeling can either decrease or increase expression (see Bintu et al., 2016; Keung & Khalil, 2016).

Figure 2.19 Two frequently studied epigenetic mechanisms. Histone remodeling involves modifications to a histone protein (around which DNA is coiled). DNA methylation involves the attachment of a methyl group to DNA. Both DNA methylation and histone remodeling can either decrease or increase gene expression.



- So much interest has been generated by epigenetics research that a world-wide effort is now underway to catalogue the epigenome of each cell type. An **epigenome** represents a catalogue of all the modifications to DNA within a particular cell type other than changes to the nucleotide base sequence (see Romanoski et al., 2015). As of 2018, the epigenomes of over 600 cell types had been characterized (see Esteller, 2018).
- Some epigenetic effects involve post-transcription alterations to RNA that do not affect the RNA base sequence. This occurs in all RNA molecules that have been examined to date, though special attention has been paid to epigenetic modifications of messenger RNA and transfer RNA. The high prevalence of these RNA modifications has led to a new effort: The cataloguing of the so-called *epitranscriptomes* of various cell types. The **epitranscriptome** of a cell refers to all those modifications of RNA that occur after transcription—that do not involve modifications to the RNA base sequence (see Bludau et al., 2019; Helm & Motorin, 2017).
- Remarkably, epigenetic mechanisms (e.g., DNA methylation, histone remodeling) can be induced by particular experiences (e.g., neural activity, hormonal state, changes to the environment) and can last a lifetime (Campbell & Wood, 2019; Handel & Ramagopalan, 2010; Nadeau, 2009; Nelson & Nadeau, 2010; Riccio, 2010; Sweatt, 2013).

It is clear that epigenetic mechanisms can produce enduring changes in an individual. But can those experience-induced changes be passed on to future generations? That is, can the experiences of your mother and father be passed on to you and on to your children? Biologists first observed such transgenerational epigenetic effects in plants, but such effects have now been observed in mammals as well. **Transgenerational epigenetics** is a subfield of epigenetics that examines the transmission of experiences via epigenetic mechanisms across generations (see Hughes, 2014). For example, it has been shown that when mice experience an odor associated with a painful shock, the memory of that experience is passed on to subsequent generations through epigenetic mechanisms (see Dias et al., 2015; Dias & Ressler, 2014; Szyf, 2014; Welberg, 2014). There is growing evidence that inheritance via transgenerational epigenetic mechanisms can also occur in humans (see Yeshurun & Hannan, 2018). Indeed, it would be an evolutionary advantage to be able to rapidly pass on any new adaptations to a changing environment (see Lowdon, Jang, & Wang, 2016; Yeshurun & Hannan, 2018).

Before leaving this subsection on epigenetics, pause to consider the important implications of what you have just learned. It now seems likely that each person's genetic material changes through life as experiences accumulate, and there is evidence that these experience-induced changes can be passed on to future generations. These findings have revolutionized the field of genetics and have major implications for how we think about our ancestors, ourselves, and our descendants.

Journal Prompt 2.3

What implications might the study of epigenetics have for researchers who are trying to determine the genetic bases of a particular psychiatric disorder?

Scan Your Brain

Do you remember what you have just read about genetics so that you can move on to the next module with confidence? To find out, fill in the following blanks with the most appropriate terms. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. According to Mendel's experiments, the dominant trait will result in about _____ of the offsprings in the second generation.
2. An offspring's observable traits are called its _____ while its genetic material is referred to as _____.
3. A single trait is controlled by two expressions of the same gene called _____.
4. Egg and sperm cells are also called _____, and each contains half the usual number of chromosomes.
5. During fertilization, the resulting _____ contains a full set of chromosomes.
6. The four nucleotide bases in DNA are adenine, thymine, cytosine, and _____.
7. Accidental errors in individual genes are called _____.
8. _____ are stretches of DNA that control the process of gene expression.
9. _____ mechanisms such as DNA methylation and histone remodeling may control gene.
10. The shape of DNA can be influenced by the change of shape of the adjacent _____.
11. All chromosomes except _____ chromosomes come in matched pairs.
12. The first phase of gene expression involves the transcription of DNA to RNA, and the second phase involves the _____ of RNA base-sequence code into a sequence of amino acids.
13. The Human Genome Project discovered that only _____ percent of human DNA contains protein-encoding genes.

Scan Your Brain answers: (1) three-quarters, (2) phenotype, genotype, (3) alleles, (4) gametes, (5) zygote, (6) guanine, (7) mutations, (8) Promoters, (9) Epigenetic, (10) histones, (11) sex, (12) translation, (13) 1.

Epigenetics of Behavioral Development: Interaction of Genetic Factors and Experience

This module comprises two classic examples of how genetic factors and experience interact to direct behavioral ontogeny. (**Ontogeny** is the development of individuals over their life span; **phylogeny**, in contrast, is the evolutionary development of species through the ages.) In each example, you will see that development is a product of the interaction of genetic and experiential factors, which we now know is likely mediated by epigenetic mechanisms (see Sweatt, 2013).

Selective Breeding of "Maze-Bright" and "Maze-Dull" Rats

LO 2.13 Discuss what insights into the genetics of behavior were gained from early research on selective breeding.

You have already learned in this chapter that most early psychologists assumed that behavior develops largely through learning. Tryon (1934) undermined this assumption by showing that behavioral traits can be selectively bred.

Tryon focused his selective-breeding experiments on the behavior that had been the focus of early psychologists in their investigations of learning: the maze running of laboratory rats. Tryon began by training a large heterogeneous group of laboratory rats to run a complex maze; the rats received a food reward when they reached the goal box. Tryon then mated the females and males that least frequently entered incorrect alleys during training—he referred to these rats as *maze-bright*. And he bred the females and males that most frequently entered incorrect alleys during training—he referred to these rats as *maze-dull*.

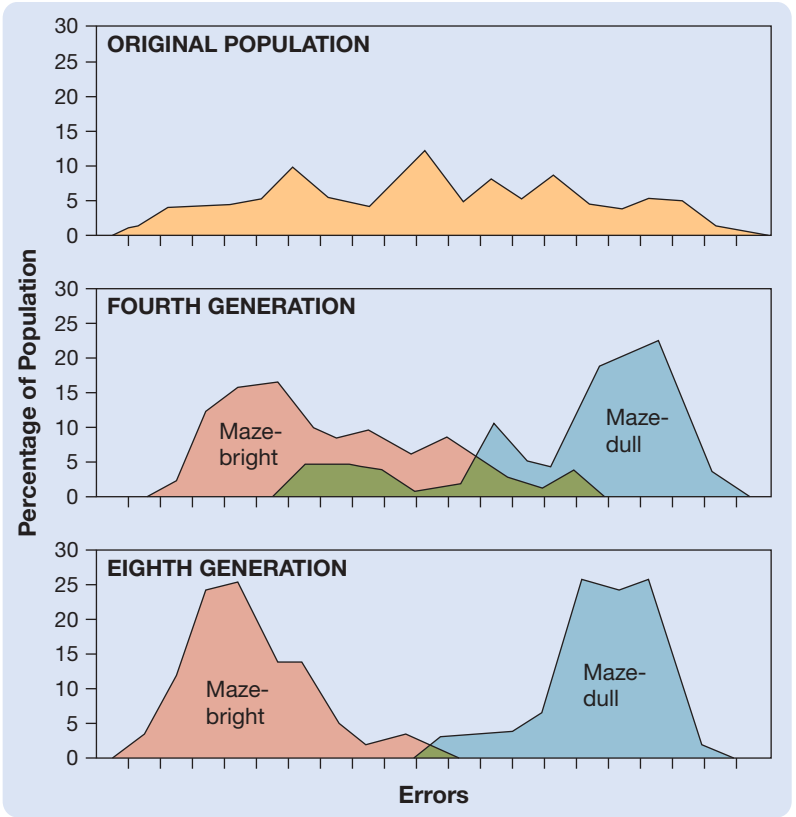
When the offspring of both the maze-bright and the maze-dull rats matured, their maze-learning performance was assessed. Then, the brightest of the maze-bright offspring were mated with one another, as were the dullest of the maze-dull offspring. This selective breeding procedure was continued for 21 generations. By the eighth generation, there was almost no overlap in the maze-learning performance of the two strains. With a few exceptions, the worst of the maze-bright strain made fewer errors than the best of the maze-dull strain (see Figure 2.20).

To control for the possibility that good maze-running performance was somehow being passed from parent to offspring through learning, Tryon used a *cross-fostering control procedure*: He tested maze-bright offspring that had been reared by maze-dull parents and maze-dull offspring that had been reared by maze-bright parents. However, the offspring of maze-bright rats made few errors even when they were reared by maze-dull rats, and the offspring of maze-dull rats made many errors even when they were reared by maze-bright rats.

Since Tryon's seminal selective-breeding experiments, many behavioral traits have been selectively bred. Indeed, it appears that any measurable behavioral trait that varies among members of a species can be selectively bred.

An important general point made by studies of selective breeding is that selective breeding based on one behavioral trait usually brings a host of other behavioral traits along with it. This indicates that the behavioral trait used as the criterion for selective breeding is not the only behavioral trait influenced by the genes segregated by the breeding. Indeed, Searle (1949) compared maze-dull and maze-bright rats on 30 different behavioral tests and found that they differed on many of them. The pattern of differences suggested that the maze-bright rats were superior maze learners not

Figure 2.20 Selective breeding of maze-bright and maze-dull strains of rats by Tryon (1934).



Data from Cooper, R. M., & Zubek, J. P. (1958)

because they were more intelligent but because they were less fearful—a trait that is not adaptive in many natural environments.

Selective-breeding studies have proved that genes influence the development of behavior. This conclusion in no way implies that experience does not. This point was driven home by Cooper and Zubek (1958) in a classic study of maze-bright and maze-dull rats. The researchers reared maze-bright and maze-dull rats in one of two environments: (1) an impoverished environment (a barren wire-mesh group cage) or (2) an enriched environment (a wire-mesh group cage that contained tunnels, ramps, visual displays, and other objects designed to stimulate interest). When the maze-dull rats reached maturity, they made significantly more errors than the maze-bright rats only if they had been reared in the impoverished environment (see Figure 2.21).

Phenylketonuria: A Single-Gene Metabolic Disorder

LO 2.14 Explain how classic research on phenylketonuria (PKU) has informed our understanding of the genetics of behavior.

It is often easier to understand the genetics of a behavioral disorder than it is to understand the genetics of typical behavior. The reason is that many genes influence the development of a typical behavioral trait, but it sometimes takes only one abnormal gene to screw it up. A good example of this point is the neurological disorder **phenylketonuria (PKU)**.

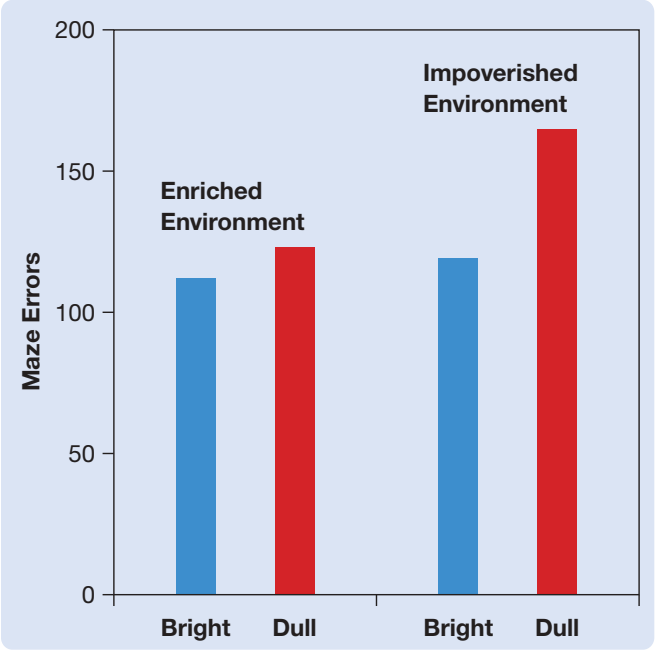
PKU was discovered in 1934 when a Norwegian dentist, Asbjørn Følling, noticed a peculiar odor in the urine of his two intellectually disabled children. He correctly assumed that the odor was related to their disorder, and he had their urine analyzed. High levels of **phenylpyruvic acid** were found in both samples. Spurred on by his discovery, Følling identified other intellectually disabled children who had abnormally high levels of urinary phenylpyruvic acid, and he concluded that this subpopulation of intellectually disabled children was suffering from the same disorder. In addition to intellectual disability, the symptoms of PKU include vomiting, seizures, hyperactivity, irritability, and brain damage (Strisciuglio & Concolino, 2014).

The pattern of transmission of PKU through the family trees of afflicted individuals indicates that it is transmitted by a single gene mutation. About 1 in 100 people of European descent carry the PKU gene; but because the gene is recessive, PKU develops only in homozygous individuals (those who inherit a PKU gene from both their mother and their father). In the United States, about 1 in 16,000 infants is born with PKU (see Bilder et al., 2016). The incidence of PKU is lower in African Americans and Asian Americans than it is for Americans of European descent.

The biochemistry of PKU turned out to be reasonably straightforward. PKU homozygotes lack *phenylalanine hydroxylase*, an enzyme required for the conversion of the amino acid *phenylalanine* to *tyrosine*. As a result, phenylalanine accumulates in the body; and levels of *dopamine*, a neurotransmitter normally synthesized from tyrosine, are particularly low (see Boot et al., 2017). The consequence is abnormal brain development.

Like other behavioral traits, the behavioral symptoms of PKU result from an interaction between genetic and environmental factors: between the PKU gene and diet (see Rohde et al., 2014). Accordingly, in most modern hospitals, the blood of newborn infants is routinely screened for high phenylalanine levels (see Casey, 2013). If the level is high, the infant is immediately placed on a special phenylalanine-restricted diet; this diet reduces both the amount of phenylalanine in the blood and the development of intellectual disabilities—however, it does not prevent the development of subtle cognitive deficits (see Brown & Lichter-Konecki, 2016). The timing of this treatment is extremely important. The phenylalanine-restricted diet does not significantly reduce the development of intellectual disabilities in PKU homozygotes unless it is initiated within the first few weeks of life; conversely, the restriction of phenylalanine in the diet is often relaxed in adulthood, with few obvious adverse consequences to the patient. The period, usually early in life, during which a particular experience must occur to have a major effect on the development of a trait is the **sensitive period** for that trait.

Figure 2.21 Maze-dull rats did not make significantly more errors than maze-bright rats when both groups were reared in an enriched environment.



Data from Cooper, R. M., & Zubek, J. P. (1958)

Genetics of Human Psychological Differences

So far, this chapter has focused on three topics: human evolution, genetics, and the interaction of genetics and experience through epigenetic mechanisms. All three topics converge on one fundamental question: Why are we the way we are?

You have learned that each of us is a product of gene–experience interactions and that the effects of genes and experience on individual development are inseparable. This final module of the chapter continues to look at the effects of gene–experience interactions, but it focuses on a developmental issue that is fundamentally different from the ones we have been discussing: the development of individual differences rather than the development of individuals.

Development of Individuals versus Development of Differences among Individuals

LO 2.15 Explain why it is important to distinguish between the development of individuals and the development of individual differences.

This chapter has so far focused on the development of individuals. The remainder of the chapter deals with the development of differences among individuals. In the development of individuals, the effects of genes and experience are inseparable. In the development of differences among individuals, they are separable. This distinction is extremely important, but it confuses many people. Let's return to the musician metaphor to explain it.

The music of an individual musician is the product of the interaction of the musician and the instrument, and it doesn't make sense to ask what proportion of the music is produced by the musician and what proportion by the instrument. However, if we evaluated the playing of a large sample of musicians, each playing a different instrument, we could statistically estimate the degree to which the differences in the quality of the music they produced resulted from differences in the musicians themselves as opposed to differences in their instruments. For example, if we selected 100 people at random and had each one play a different professional-quality guitar, we would likely find that most of the variation in the quality of the music resulted from differences in the participants, some being experienced players and some never having played before. In the same way, researchers can select a group of volunteers and ask what proportion of the variation among them in some attribute (e.g., intelligence) results from genetic differences as opposed to experiential differences.

To assess the relative contributions of genes and experience to the development of differences in psychological attributes, behavioral geneticists study individuals of known genetic similarity. For example, they often compare **monozygotic twins**, who developed from the same zygote and thus are genetically similar, with **dizygotic twins**, who developed from two zygotes and thus are no more similar than any pair of *siblings* (brothers and sisters). Studies of pairs of monozygotic and dizygotic twins who have been separated at infancy by adoption are particularly informative about the relative contributions of genes and experience to differences in human psychological development. The most extensive of such adoption studies is the Minnesota Study of Twins Reared Apart (see Bouchard & Pedersen, 1999).

Heritability Estimates: Minnesota Study of Twins Reared Apart

LO 2.16 Explain heritability estimates and how they are commonly misinterpreted.

The Minnesota Study of Twins Reared Apart involved 59 pairs of monozygotic twins and 47 pairs of dizygotic twins who had been reared apart as well as many pairs of monozygotic and dizygotic twins who had been reared together. Their ages ranged from 19 to 68. Each twin was brought to the University of Minnesota for approximately 50 hours of testing, which focused on the assessment of intelligence and personality. Would the adult monozygotic twins reared apart prove to be similar because they were genetically similar, or would they prove to be different because they had been brought up in different environments?

The results of the Minnesota Study of Twins Reared Apart proved to be remarkably consistent—both internally, between the various cognitive and personality dimensions that were studied, and externally, with the findings of other studies. In general, adult monozygotic twins were substantially more similar to one another on all psychological dimensions than were adult dizygotic twins, whether or not both twins of a pair were raised in the same family environment (see Turkheimer, 2000).

In order to quantify the contributions of genetic variations in a particular study, such as the Minnesota Study of Twins Reared Apart, researchers often calculate heritability estimates. A **heritability estimate** is not about individual development; it is a numerical estimate of the proportion of variability that occurred in a particular trait in a particular study as a result of the genetic variation in that study (see Turkheimer, Pettersson, & Horn, 2014). Heritability estimates tell us about the contribution of genetic differences to phenotypic differences among the participants in a study; they have nothing to say about the relative contributions of genes and experience to the development of individuals.

The concept of heritability estimates can be quite confusing. We suggest that you pause here and carefully think about the definition before proceeding. The musician metaphor may help you here (see page 48). Recall that music is the product of an interaction between the musician and instrument. We cannot ask what proportion of that music is from the instrument and what proportion is from the musician. However, let's say we have many musicians and we listen to each make their music. We can now ask: What proportion of the differences among their music is due to their instruments and what proportion is due to their musical skills? Likewise, in the study of intelligence in many individuals, we can ask: What proportion of the differences in intelligence is due to differences in their environment and what proportion is due to differences in their genetics?

This analysis raises an important point: The magnitude of a study's heritability estimate depends on the amount of genetic and environmental variation from which it was calculated, and it cannot necessarily be generalized to other groups of individuals or other situations. For example, in the Minnesota study, there was relatively little environmental variation. All participants were raised in industrialized countries (Great Britain, Canada, and the United States) by parents who met the strict standards required for adoption. Accordingly, most of the variation in the subjects' intelligence and personality resulted from genetic variation. If the twins had each been separately adopted by vastly different parents (e.g., European royalty vs. a person living in extreme poverty), the resulting heritability estimates for IQ and personality would likely have been much lower.

Now that you understand the meaning of heritability estimates, let us tell you how big they tend to be for a variety of complex human traits and behaviors: for example, for intelligence, personality traits, aggression, divorce, religious beliefs, sports participation, psychiatric disorders, and television watching. The answer is simple because heritability estimates tend to be about the same regardless of the particular trait or behavior under consideration and regardless of the particular basis used to calculate them (i.e., twin, adoption, or family-tree studies). In the representative Western samples that have been studied, all complex traits and behaviors have substantial heritability estimates—most between 40 and 80 percent.

The discovery that genetic variability contributes substantially to individual differences in virtually all human traits and behaviors has led several eminent geneticists to argue that no more heritability estimate studies should be conducted (e.g., Johnson et al., 2009; Petronis, 2010). What could more heritability estimate studies possibly add? These geneticists are, however, excited about the potential of two other types of twin studies that have been increasingly reported. This chapter ends with them.

A Look into the Future: Two Kinds of Twin Studies

LO 2.17 Describe two ways that twin studies can be used to study the interaction of genes and experience (i.e., nature and nurture).

Two lines of research on twins have recently created considerable excitement among geneticists and other scholars. We hope you share their enthusiasm.

TWIN STUDIES OF EPIGENETIC EFFECTS. Most studies of epigenetic effects have focused on nonhuman species. In plants and nonhuman animals, it is quite clear that epigenetic changes can be triggered by experience, can last a lifetime, and can be passed on to future generations (see Szyf, 2014). To what extent do these amazing results apply to humans? Twin studies may provide a route to the answers (see Aguilera et al., 2010; Feil & Fraga, 2012).

The study of epigenetic effects in humans is difficult because experimental manipulation of human genetic material is not ethical. Monozygotic twins, however, provide a method of circumventing this difficulty. At conception monozygotic twins are genetically identical, and by repeatedly assessing their DNA one can document the development and survival of the many epigenetic differences that develop between them (see Bell & Saffery, 2012; Bell & Spector, 2011; Chatterjee & Morison, 2011; Silva et al., 2011). Moreover, by comparing monozygotic and dizygotic twins, it is possible to get a sense of the degree to which changes are caused by experiential as opposed to genetic factors—if epigenetic changes developed under genetic control, one would expect that the pattern of epigenetic changes would be more similar in monozygotic than dizygotic pairs.

The first systematic demonstration of epigenetic differences in human twins was published by Fraga and colleagues (2005). They took tissue samples (blood, skin, muscle) from 40 pairs of monozygotic twins, ranging in age from 3 to 74. Then, they screened the tissues for epigenetic alterations (e.g., DNA methylation, histone remodeling). They found that the twins were epigenetically indistinguishable early in life, but differences between them accumulated as they aged, each type of tissue displaying a different epigenetic profile (see Zong et al., 2012). As a result, the former assumption that monozygotic twins are genetically identical was disproven, and the common practice of referring to monozygotic twins as *identical twins* should be curtailed (see Figure 2.22).

In another study of epigenetic changes in twins, Wong and colleagues (2010) examined DNA methylation in *buccal cells* (cells of the lining of the mouth) scraped from 46 pairs of monozygotic twins and 45 pairs of dizygotic twins. They took samples from the twins at age 5 and again from the same twins at age 10. Then they assessed DNA methylation. Wong and colleagues found DNA methylation to be

Figure 2.22 Epigenetic research suggests that the common practice of referring to monozygotic twins as "identical twins" is no longer appropriate.

J. Lee/Getty Images

prominent in both groups of twins at both ages. Because the concordance rates of DNA methylation were the same between monozygotic twins and between dizygotic twins, they concluded that differences in DNA methylation are mainly a consequence of experiential factors.

The discovery of epigenetic differences in monozygotic twins raises the possibility that epigenetic differences may explain why one twin develops a disease and the other doesn't (Bell & Spector, 2011; Haque, Gottesman, & Wong, 2009). Once identified, such epigenetic differences would provide important clues to the causes and mechanisms of the disease. Bell and Spector (2011) suggest that *disease-discordant monozygotic twin studies* are a particularly powerful approach (see also Czyz et al., 2012). This kind of study begins with the identification of monozygotic twins who are discordant for a disease of interest. Then one searches each pair for epigenetic differences focusing on those areas of DNA that are thought to be involved in the disorder. Large-scale studies in monozygotic twins across different ages, tissues, and epigenetic effects could greatly improve our understanding of human disease (see Bell & Spector, 2011; Tan et al., 2014).

TWIN STUDIES OF THE EFFECTS OF EXPERIENCE ON HERITABILITY. In thinking about heritability estimates, it is paramount to remember that heritability estimates depend on the particular conditions and subjects of a particular study. This point was driven home by the influential study of Turkheimer and colleagues (2003). Before the Turkheimer et al. study, all published studies of the heritability of intelligence were conducted on middle- to upper-class families, and the heritability estimates for intelligence tended to be about 75 percent.

Turkheimer and colleagues assessed heritability of intelligence in two samples of 7-year-old twins: those from families of low socioeconomic status (SES) and those from families of middle to high SES. The heritability estimates for intelligence in the middle- to high-SES twins was, as expected, about 70 percent. However, the heritability estimate for intelligence in the twins from low-SES families was only 10 percent. This effect was subsequently replicated and extended to other age groups: babies (Tucker-Drob et al., 2011) and adolescents (Harden, Turkheimer, & Loehlin, 2007).

One major implication of the study of Turkheimer et al. (2003) is that it forces us to think about intelligence as developing from the interaction of genes and experience, not from one or the other. It seems that one can inherit the potential to be of superior intelligence, but this potential is rarely realized in a poverty-stricken environment (see Nisbett et al., 2012).

This finding also has important implications for the development of programs to help the poor. Many politicians have argued against special programs for the poor because most heritability estimates of intelligence are high. They incorrectly argue that because intelligence is largely inherited (i.e., it has a high heritability estimate), special programs for the poor are a waste of money. However, the findings of Turkheimer and colleagues suggest otherwise: Reducing poverty would mean that all children would be able to reach their intellectual potential.

Themes Revisited

This chapter introduced the topics of evolution, genetics, and development, but two themes prevailed: thinking about epigenetics and thinking creatively about the biology of behavior. In terms of thinking about epigenetics, you were fully introduced to the field of epigenetics and you learned about how that field has huge implications for our understanding of behavior. This chapter also challenged you to think about important biopsychological phenomena in creative new ways: the nature–nurture issue, the physiological-or-psychological dichotomy, the genetics of human psychological differences, the meaning of heritability estimates, and the important study of Turkheimer and colleagues (2003).

Two other themes also received coverage in this chapter: the evolutionary perspective and clinical implications. The evolutionary perspective was illustrated by comparative research on self-awareness in chimps and by consideration

of the evolutionary significance of social dominance and courtship displays. The clinical implications theme was illustrated by the case of the man who fell out of bed, the discussion of phenylketonuria (PKU), and the discussion of disease-discordant twin studies.

This chapter was jam-packed with examples of one of the emerging themes: thinking about epigenetics. You were fully introduced to the field of epigenetics and you learned about how the field has huge implications for our understanding of behavior.

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Chapter 3

Anatomy of the Nervous System

Systems, Structures, and Cells That Make Up Your Nervous System

Mike Kemp/Tetra Images/Alamy Stock Photo

Chapter Overview and Learning Objectives

General Layout of the Nervous System	**LO 3.1** List and describe the major divisions of the nervous system.
	LO 3.2 Describe the three meninges and explain their functional role.
	LO 3.3 Explain where cerebrospinal fluid is produced and where it flows.
	LO 3.4 Explain what the blood–brain barrier is and what functional role it serves.
Cells of the Nervous System	**LO 3.5** Draw, label, and define the major features of a multipolar neuron.

	LO 3.6 Briefly describe four kinds of glial cells.
Neuroanatomical Techniques and Directions	**LO 3.7** Compare several neuroanatomical research techniques. **LO 3.8** Illustrate the neuroanatomical directions.
Anatomy of the Central Nervous System	**LO 3.9** Draw and label a cross section of the spinal cord. **LO 3.10** List and discuss the five major divisions of the human brain. **LO 3.11** List and describe the components of the myelencephalon. **LO 3.12** List and describe the components of the metencephalon. **LO 3.13** List and describe the components of the mesencephalon. **LO 3.14** List and describe the components of the diencephalon. **LO 3.15** List and describe the components of the telencephalon. **LO 3.16** List and describe the components of the limbic system and of the basal ganglia.

In order to understand what the brain does, it is first necessary to understand what it is—to know the names and locations of its major parts and how they are connected to one another. This chapter introduces you to these fundamentals of brain anatomy.

Before you begin this chapter, we want to apologize for the lack of foresight displayed by early neuroanatomists in their choice of names for neuroanatomical structures—but how could they have anticipated that Latin and Greek, universal languages of the educated in their day, would not be compulsory university fare in our time? To help you, we have provided the literal English meanings of many of the neuroanatomical terms, and we have kept this chapter as brief, clear, and to the point as possible, covering only the most important structures. The payoff for your effort will be a fundamental understanding of the structure of the human brain and a new vocabulary to discuss it.

General Layout of the Nervous System

In this module, we'll cover the general layout of the nervous system. We'll begin by discussing its two main divisions. Then, we'll look at the roles of meninges, ventricles, and cerebrospinal fluid. We'll conclude with a look at the blood–brain barrier.

Divisions of the Nervous System

LO 3.1 List and describe the major divisions of the nervous system.

The vertebrate nervous system is composed of two divisions: the central nervous system and the peripheral nervous system (see Figure 3.1). Roughly speaking, the **central nervous system (CNS)** is the division of the nervous system located within the skull and spine, and the **peripheral nervous system (PNS)** is the division located outside the skull and spine.

The central nervous system is composed of two divisions: the brain and the spinal cord. The *brain* is the part of the CNS located in the skull; the *spinal cord* is the part located in the spine.

The peripheral nervous system is also composed of two divisions: the somatic nervous system and the autonomic nervous system. The **somatic nervous system (SNS)** is the part of the PNS that interacts with the external environment. It is composed of **afferent nerves** that carry sensory signals from the skin, skeletal muscles, joints, eyes, ears, and so on, to the central nervous system and **efferent nerves** that carry motor signals from the central nervous system to the skeletal muscles. The **autonomic nervous system (ANS)** is the part of the peripheral nervous system that regulates the body's internal environment. It is composed of afferent nerves that carry sensory signals from internal organs to the CNS and efferent nerves that carry motor signals from the CNS to internal organs. You will not confuse the

Figure 3.1 The human central nervous system (CNS) and peripheral nervous system (PNS). The CNS is represented in red; the PNS in orange. Notice that even those portions of nerves that are within the spinal cord are considered to be part of the PNS.

terms *afferent* and *efferent* if you remember that many words that involve the idea of going toward something—in this case, going toward the CNS—begin with an *a* (e.g., *advance, approach, arrive*) and that many words that involve the idea of going away from something begin with an *e* (e.g., *exit, embark, escape*).

The autonomic nervous system has two kinds of efferent nerves: sympathetic nerves and parasympathetic nerves. The **sympathetic nerves** are autonomic motor nerves that project from the CNS in the *lumbar* (small of the back) and *thoracic* (chest area) regions of the spinal cord. The **parasympathetic nerves** are those autonomic motor nerves that project from the brain and *sacral* (lower back) region of the spinal cord. See Appendix I. (Ask your instructor to specify the degree to which you are responsible for material in the appendices.) All sympathetic and parasympathetic nerves are two-stage neural paths: The sympathetic and parasympathetic neurons project from the CNS and go only part of the way to the target organs before they *synapse on* other neurons (second-stage neurons) that carry the signals the rest of the way. However, the sympathetic and parasympathetic systems differ in that the sympathetic neurons project from the CNS synapse on second-stage neurons at a substantial distance from their target organs, whereas the parasympathetic neurons project from the CNS synapse near their target organs on very short second-stage neurons (see Appendix I).

The conventional view of the respective functions of the sympathetic and parasympathetic systems stresses three important principles: (1) sympathetic nerves stimulate, organize, and mobilize energy resources in threatening situations, whereas parasympathetic nerves act to conserve energy; (2) each autonomic target organ receives opposing sympathetic and parasympathetic input, and its activity is thus controlled by relative levels of sympathetic and parasympathetic activity; and (3) sympathetic changes are indicative of psychological arousal, whereas parasympathetic changes are indicative of psychological relaxation. Although these principles are generally correct, there are significant qualifications and exceptions to each of them (see Guyenet, 2006)—see Appendix II.

Most of the nerves of the peripheral nervous system project from the spinal cord, but there are 12 pairs of exceptions: the 12 pairs of **cranial nerves**, which project from the brain. They are numbered in sequence from front to back. The cranial nerves include purely sensory nerves such as the olfactory nerves (I) and the optic nerves (II), but most contain both sensory and motor fibers. The longest cranial nerves are the vagus nerves (X), which contain motor and sensory fibers traveling to and from the gut. The 12 pairs of cranial nerves and their targets are illustrated in Appendix III; the functions of these nerves are listed in Appendix IV. The autonomic motor fibers of the cranial nerves are parasympathetic.

The functions of the various cranial nerves are commonly assessed by neurologists as a basis for diagnosis. Because the functions and locations of the cranial nerves are specific, disruptions of particular cranial nerve functions provide excellent clues about the location and extent of tumors and other kinds of brain pathology.

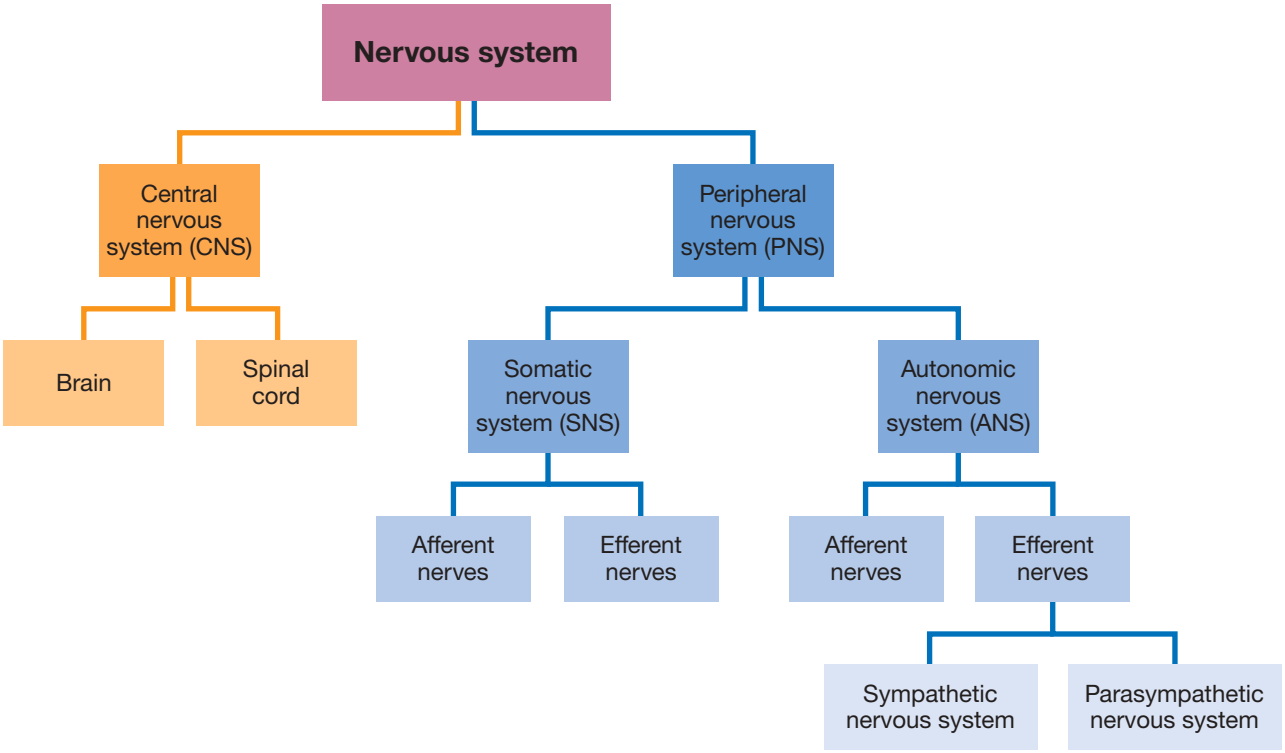
Figure 3.2 summarizes the major divisions of the nervous system. Notice that the nervous system is a "system of twos."

Meninges

LO 3.2 Describe the three meninges and explain their functional role.

The brain and spinal cord (the CNS) are the most protected organs in the body. They are encased in bone and covered by three protective membranes, the three **meninges** (pronounced "men-IN-gees"; see Coles et al., 2017). The outer *meninx* (which, believe it or not, is the singular of *meninges*)

Figure 3.2 The major divisions of the nervous system.



is a tough membrane called the **dura mater** (tough mother). Immediately inside the dura mater is the fine **arachnoid membrane** (spider-web-like membrane). Beneath the arachnoid membrane is a space called the **subarachnoid space**, which contains many large blood vessels and cerebrospinal fluid; then comes the innermost meninx, the delicate **pia mater** (pious mother), which adheres to the surface of the CNS.

Ventricles and Cerebrospinal Fluid

LO 3.3 **Explain where cerebrospinal fluid is produced and where it flows.**

Also protecting the CNS is the **cerebrospinal fluid (CSF)**, which fills the subarachnoid space, the central canal of the spinal cord, and the cerebral ventricles of the brain. The **central canal** is a small central channel that runs the length of the spinal cord; the **cerebral ventricles** are the four large internal chambers of the brain: the two lateral ventricles, the third ventricle, and the fourth ventricle (see Figure 3.3). The subarachnoid space, central canal, and cerebral ventricles are interconnected by a series of openings and thus form a single reservoir.

The cerebrospinal fluid supports and cushions the brain. Patients who have had some of their cerebrospinal fluid drained away often suffer raging headaches and experience stabbing pain each time they jerk their heads.

According to the traditional view, cerebrospinal fluid is produced by the **choroid plexuses** (networks of *capillaries*, or small blood vessels that protrude into the ventricles from the pia mater), and the excess cerebrospinal fluid is continuously absorbed from the subarachnoid space into large blood-filled spaces, or *dural sinuses*, which run through the dura mater and drain into the large jugular veins of the neck. However, there is growing appreciation that cerebrospinal fluid production and absorption are more complex than was originally thought (see Brinker et al., 2014). Figure 3.4 illustrates the absorption of cerebrospinal fluid from the subarachnoid space into the large sinus that runs along the top of the brain between the two cerebral hemispheres.

Occasionally, the flow of cerebrospinal fluid is blocked by a tumor near one of the narrow channels that link the ventricles—for example, near the *cerebral aqueduct*, which connects the third and fourth ventricles. The resulting buildup of fluid in the ventricles causes the walls of the ventricles, and thus the entire brain, to expand, producing a condition called *hydrocephalus* (water head). Hydrocephalus is treated by draining the excess fluid from the ventricles and trying to remove the obstruction.

Journal Prompt 3.1

Hydrocephalus is often congenital (present from birth). What do you think might be some of the long-term effects of being born with hydrocephalus?

Figure 3.3 The cerebral ventricles and central canal.

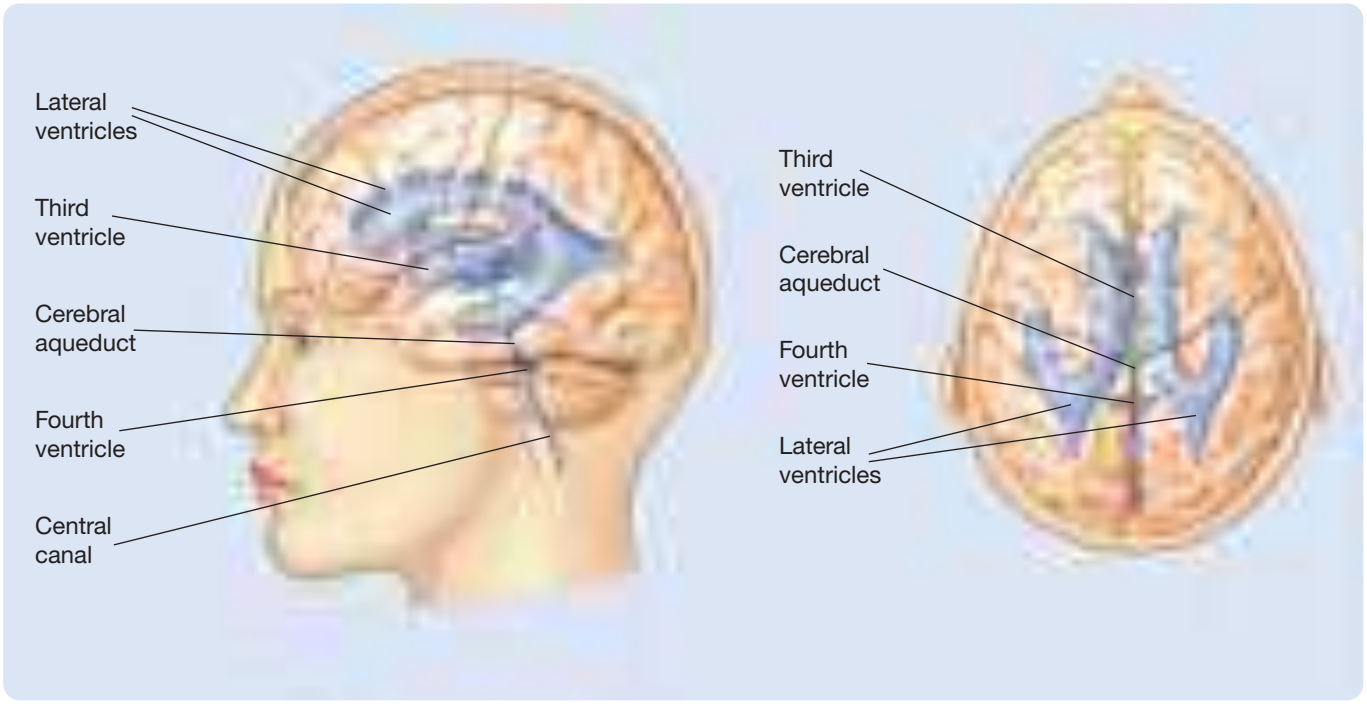
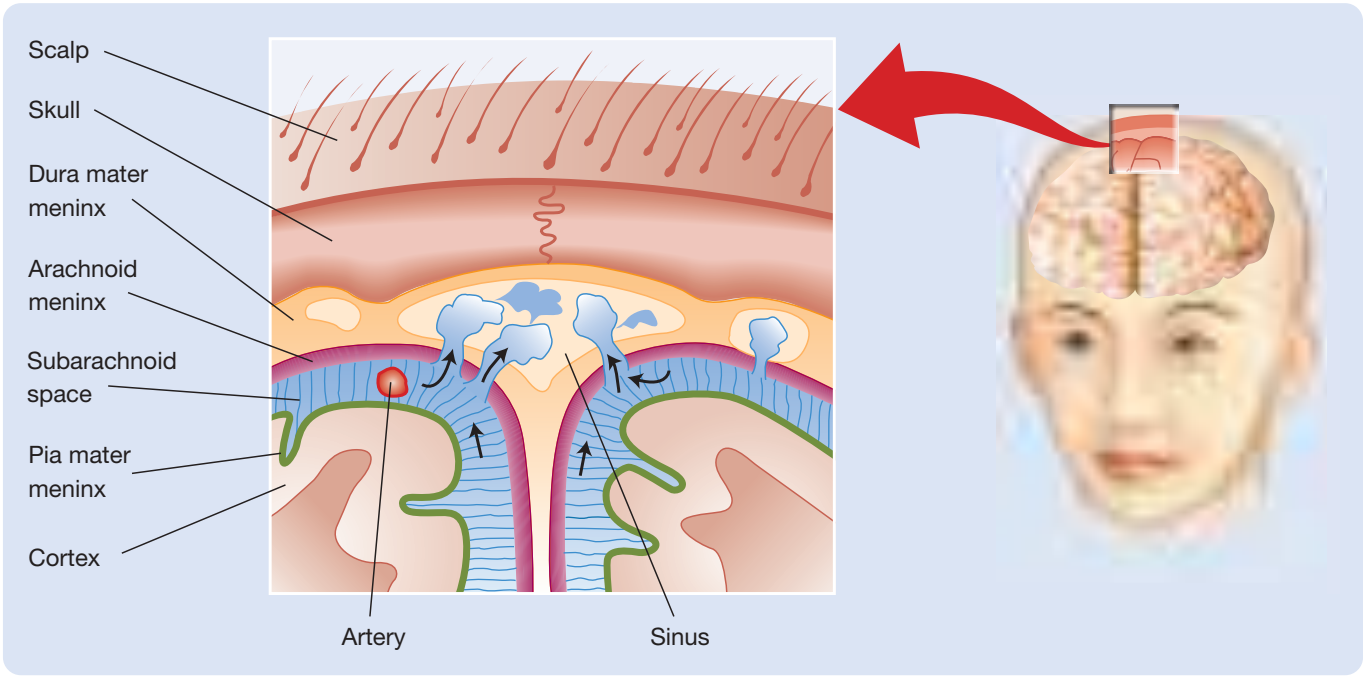


Figure 3.4 The absorption of cerebrospinal fluid (CSF) from the subarachnoid space (blue) into a major sinus. Note the three meninges.



Blood–Brain Barrier

LO 3.4 **Explain what the blood–brain barrier is and what functional role it serves.**

The brain is a finely tuned electrochemical organ whose function can be severely disturbed by the introduction of certain kinds of chemicals. Fortunately, a mechanism impedes the passage of many toxic substances from the blood into the brain: the **blood–brain barrier**. This barrier is a consequence of the special structure of cerebral blood vessels. In the rest of the body, the cells that compose the walls of blood vessels are loosely packed; as a result, most

molecules pass readily through them into surrounding tissue. In the brain, however, the cells of the blood vessel walls are tightly packed, thus forming a barrier to the passage of many molecules—particularly proteins and other large molecules (see Chow & Gu, 2015). The degree to which therapeutic or recreational drugs can influence brain activity depends on the ease with which they penetrate the blood–brain barrier (see Interlandi, 2013; Siegenthaler, Sohet, & Daneman, 2013).

The blood–brain barrier does not impede the passage of all large molecules. Some large molecules that are critical for normal brain function (e.g., glucose) are actively transported through cerebral blood vessel walls. Also, the blood vessel walls in some areas of the brain allow certain large molecules to pass through them unimpeded. Many CNS disorders are associated with impairment of the blood–brain barrier (see Bentivoglio & Kristensson, 2014; Jiang et al., 2018).

Scan Your Brain

This is a good place to pause and scan your brain to check your knowledge of the CNS. Fill in the following blanks with the most appropriate terms. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. The somatic nervous system includes _____ nerves that carry motor signals from the central nervous system to the muscles.
2. The _____ is the part of the peripheral nervous system that regulates the body's internal environment.
3. The brain and the spinal cord are the only organs that are protected with three layers of protective membranes called _____.
4. _____ or "tough mother" is the outer meninx.
5. The _____ nervous system is activated when you encounter a threatening information such as a bear attacking you. This system is essential for the initiation of fight-or-flight responses.
6. Motor nerves that project from the brain and the lower region of the spine are called _____ nerves.
7. The _____ nerve is a purely sensory nerve that transfers visual information from the retina of the eye to the brain.
8. The _____ nerve is the nerve cell that extends directly from the brain to the gut.
9. The _____ is a channel that connects the third and fourth ventricles in the brain.
10. The ventricles of patients with a congenital condition called _____ build up fluid as a result of blocked channels in the brain.
11. Many toxic substances that are present in the bloodstream are prohibited from entering the brain by a mechanism called the _____ where cells of blood vessel walls are tightly packed, forming a barrier to the passage of large proteins.
12. Unlike large toxic molecules, _____, which is critical for the function of the brain, is actively transported through the vessel walls.

Scan Your Brain answers: (1) efferent, (2) ANS, (3) meninges, (4) Dura mater, (5) sympathetic, (6) parasympathetic, (7) optic, (8) vagus, (9) cerebral aqueduct, (10) hydrocephalus, (11) blood–brain barrier, (12) glucose.

Cells of the Nervous System

Most of the cells of the nervous system are of two fundamentally different types: neurons and glial cells. Their anatomy is discussed in the following two sections.

Anatomy of Neurons

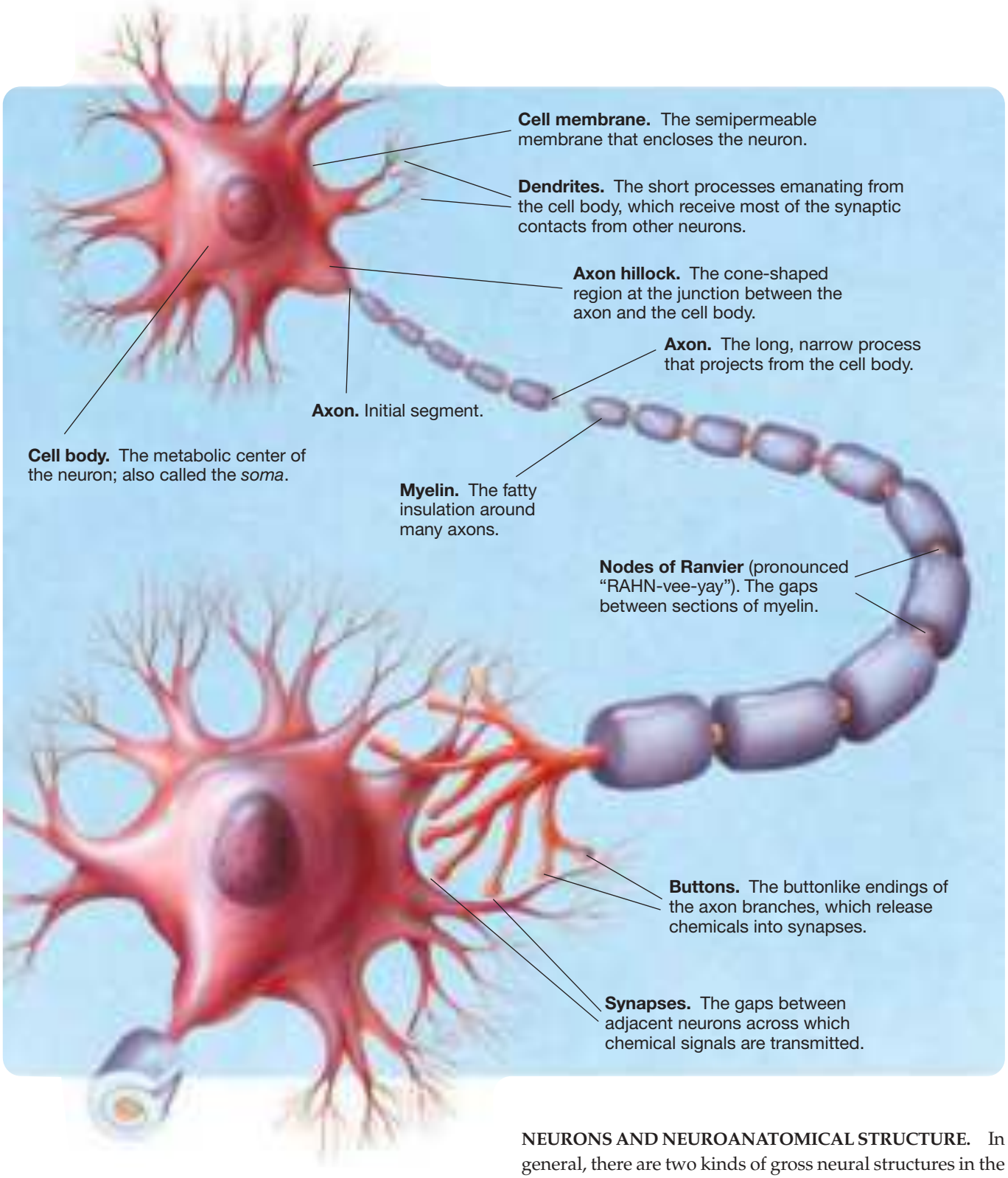
LO 3.5 Draw, label, and define the major features of a multipolar neuron.

Recall that **neurons** are cells that are specialized for the reception, conduction, and transmission of electrochemical signals. They come in an incredible variety of shapes and sizes (see Sharpee, 2014; Shen, 2015; Underwood, 2015); however, many are similar to the one illustrated in Figures 3.5 and 3.6, which detail the major external and internal features of a neuron, respectively.

NEURON CELL MEMBRANE. The neuron cell membrane is composed of a *lipid bilayer*, or two layers of fat molecules (see Figure 3.7). Embedded in the lipid bilayer are numerous protein molecules that are the basis of many of the cell membrane's functional properties. Some membrane proteins are *channel proteins*, through which certain molecules can pass; others are *signal proteins*, which transfer a signal to the inside of the neuron when particular molecules bind to them on the outside of the membrane.

CLASSES OF NEURONS. Figure 3.8 illustrates a way of classifying neurons based on the number of processes (projections) emanating from their cell bodies. A neuron with more than two processes extending from its cell body is classified as a **multipolar neuron**; most neurons are multipolar. A neuron with one process extending from its cell body is classified as a **unipolar neuron**, and a neuron with two processes extending from its cell body is classified as a **bipolar neuron**. Neurons with a short axon or no axon at all are called **interneurons**; their function is to integrate neural

Figure 3.5 The major external features of a neuron.



activity within a single brain structure, not to conduct signals from one structure to another. Classifying neurons is a complex task, and neuroscientists still don't agree on the best method of classification (see Cembrowski & Menon, 2018; Wichterle, Gifford, & Mazzoni, 2013; Zeng & Sanes, 2017).

NEURONS AND NEUROANATOMICAL STRUCTURE. In general, there are two kinds of gross neural structures in the nervous system: those composed primarily of cell bodies and those composed primarily of axons. In the central nervous system, clusters of cell bodies are called **nuclei** (singular *nucleus*); in the peripheral nervous system, they are called **ganglia** (singular *ganglion*). (Note that the word *nucleus* has two different neuroanatomical meanings; it

Figure 3.6 The major internal features of a neuron.

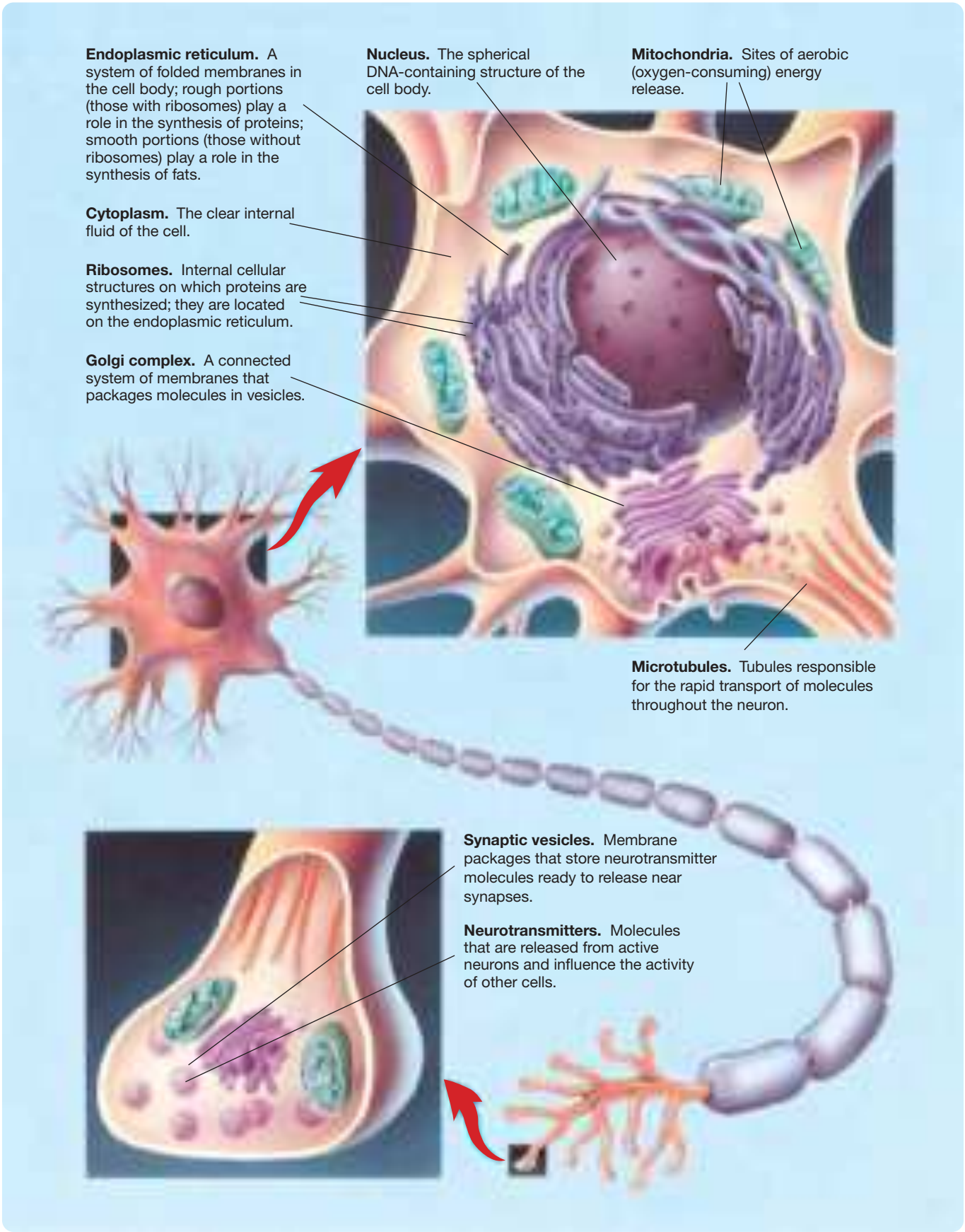


Figure 3.7 The cell membrane is a lipid bilayer with signal proteins and channel proteins embedded in it.

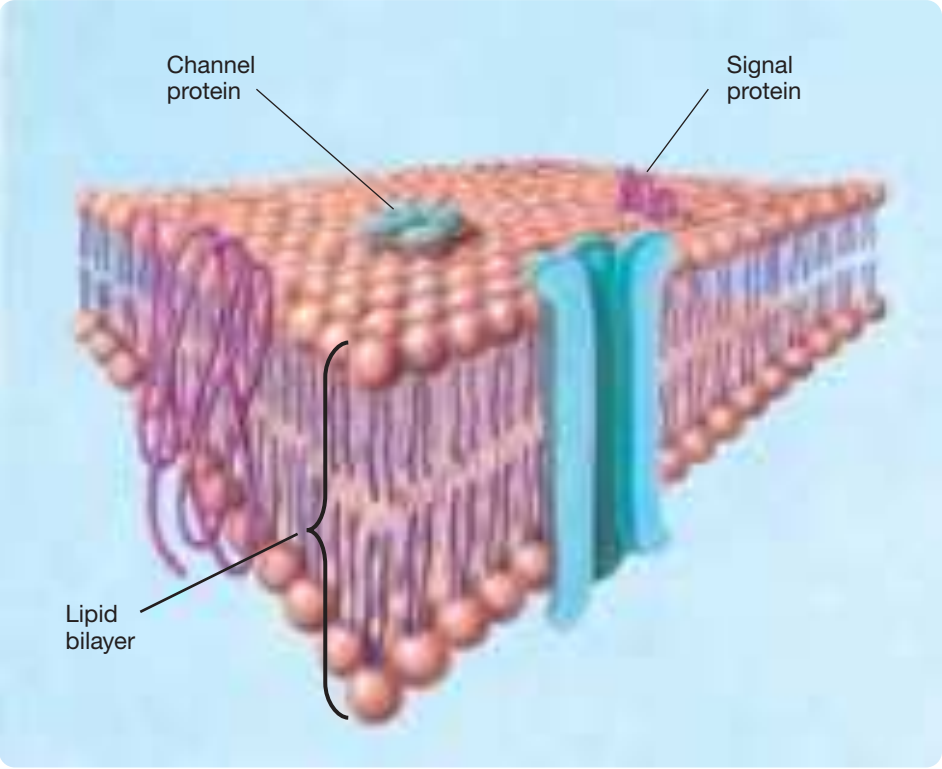
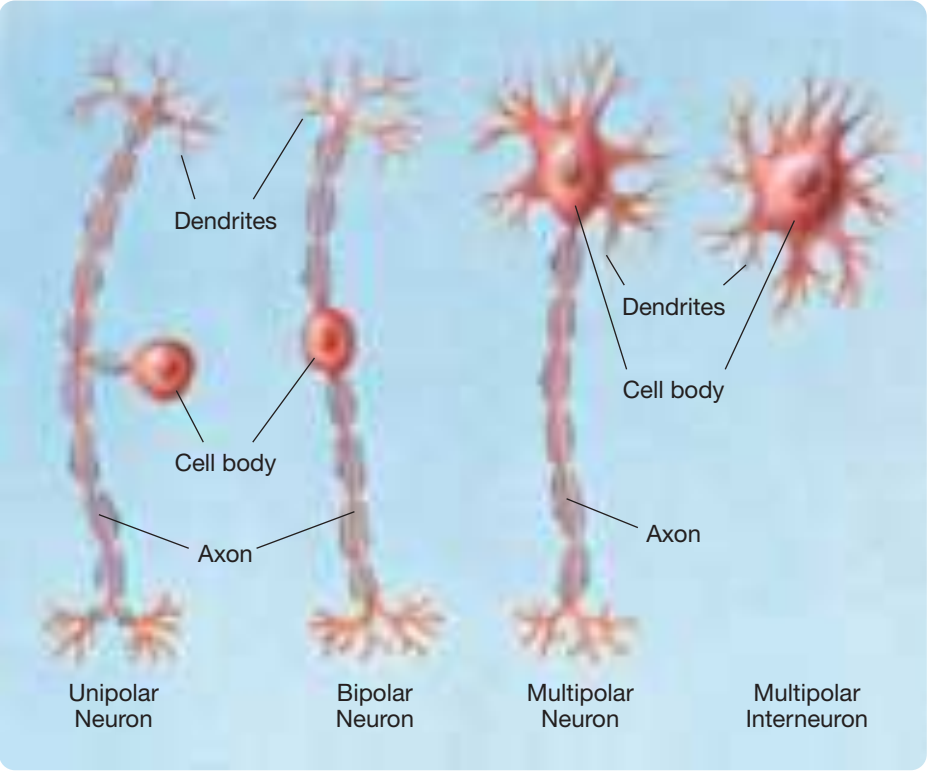


Figure 3.8 A unipolar neuron, a bipolar neuron, a multipolar neuron, and an interneuron.



is a structure in the neuron cell body and a cluster of cell bodies in the CNS.) In the central nervous system, bundles of axons are called **tracts**; in the peripheral nervous system, they are called **nerves**.

Glia: The Forgotten Cells

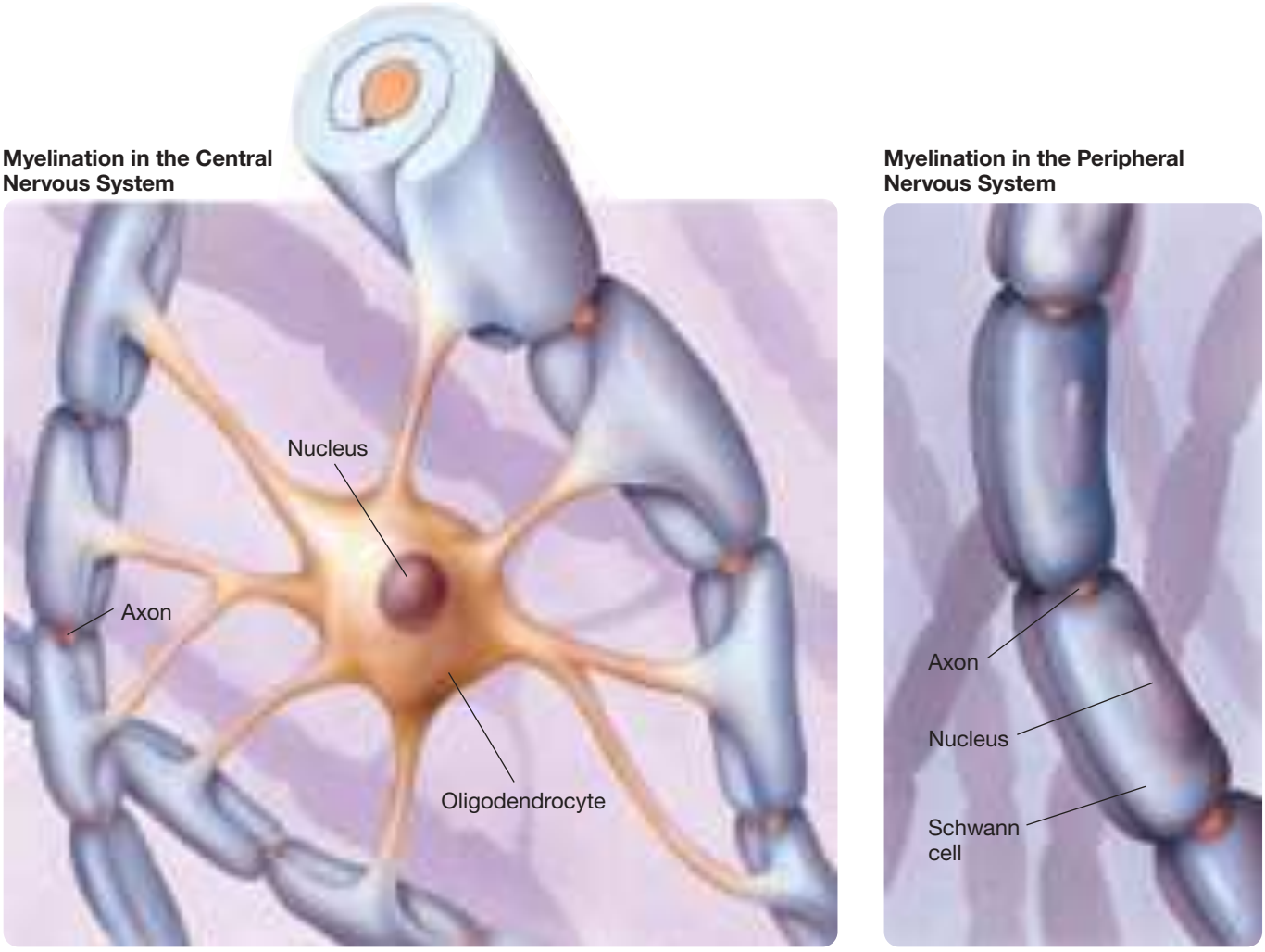
LO 3.6 Briefly describe four kinds of glial cells.

Neurons are not the only cells in the nervous system; there are about as many **glial cells**, or *glia* (pronounced "GLEE-a"). It is commonly said that there are 10 times as many glia as neurons in the human brain, but this is incorrect: There are roughly two glia for every three neurons in your brain (see Nimmerjahn & Bergles, 2015; von Bartheld, 2017).

There are several kinds of glia. **Oligodendrocytes**, for example, are glial cells with extensions that wrap around the axons of some neurons of the central nervous system. These extensions are rich in **myelin**, a fatty insulating substance, and the **myelin sheaths** they form increase the speed of axonal conduction. A similar function is performed in the peripheral nervous system by **Schwann cells**, a second class of glia. Oligodendrocytes and Schwann cells are illustrated in Figure 3.9. Notice that each Schwann cell constitutes one myelin segment, whereas each oligodendrocyte provides several myelin segments, often on more than one axon. Another important difference between Schwann cells and oligodendrocytes is that only Schwann cells can guide axonal *regeneration* (regrowth) after damage. That is why effective axonal regeneration in the mammalian nervous system is restricted to the PNS.

Microglia make up a third class of glia. Microglia are smaller than

Figure 3.9 The myelination of CNS axons by an oligodendrocyte and the myelination of PNS axons by Schwann cells.



other glial cells—thus their name. They respond to injury or disease by multiplying, engulfing cellular debris or even entire cells (see Brown & Neher, 2014), and triggering inflammatory responses (see Smith & Dragunow, 2014).

Astrocytes constitute a fourth class of glia. They are the largest glial cells, and they are so named because they are star-shaped (*astro* means "star"). The extensions of some astrocytes cover the outer surfaces of blood vessels that course through the brain; they also make contact with neurons (see Figure 3.10). These particular astrocytes appear to play a role in allowing the passage of some chemicals from the blood into CNS neurons and in blocking other chemicals (see Paixão & Klein, 2010), and they have the ability to contract or relax blood vessels based on the blood flow demands of particular brain regions (see Howarth, 2014; Mishra et al., 2016; Muoio, Persson, & Sendeski, 2014).

For decades, it was assumed that the function of glia was mainly to provide support for neurons—provide them with nutrition, clear waste, and form a physical matrix to hold neural circuits together (*glia* means "glue"). But this limited view of the role of glial cells has changed, thanks to a series of remarkable findings. For example, astrocytes, the most studied of the glial cells, have been shown to exchange chemical signals with neurons and other astrocytes (Araque et al., 2014; Montero & Orellana, 2015; Yoon & Lee, 2014), to control the establishment and maintenance of synapses between neurons (Baldwin & Eroglu, 2017), to modulate neural activity (Bouzier-Sore & Pellerin, 2013), to form functional networks with neurons and other astrocytes (Gittis & Brasier, 2015; Haim & Rowitch, 2017; Lee et al., 2014; Perea, Sur, & Araque, 2014), to control the blood–brain barrier (Alvarez, Katayama, & Prat, 2013; Cabezas et al., 2014), to respond to brain injury (Khakh & Sofroniew, 2015), and to play a role in certain forms of cognition (e.g., Dallérac & Rouach, 2016; Martin-Fernandez et al., 2017). Microglia have also been shown to play many more roles in brain function than had previously

Figure 3.10 Astrocytes (shown in pink) have an affinity for blood vessels (in red) and they also make contact with neurons (in blue).

GUNILLA ELAM/Science Source

been thought (see Pósfai et al., 2018); for example, they have been shown to play a role in the regulation of cell death (Wake et al., 2013), synapse formation (Parkhurst et al., 2013; Welberg, 2014), and synapse elimination (Wake et al., 2012).

Research on the function of glia, although still in its early stages, is creating considerable excitement. There is now substantial evidence that the physiological effects of glia are both numerous and much more important than anyone might have imagined two decades ago. For example, some researchers have suggested that *glial networks* may be the dwelling places of thoughts (see Verkhratsky, Parpura, & Rodríguez, 2010). One final important discovery about glial cells is that they are much more varied than implied by the four types that we have just described: oligodendrocytes, Schwann cells, microglia, and astrocytes. For example, a new type of glial cell was recently discovered (see Fan & Agid, 2018); and at least fifteen different kinds of astrocytes have been identified, each with its own structure, physiology, and specific locations in the brain (Chai et al., 2017; Clarke & Liddelow, 2017; Lin et al., 2017). Sorting out the functions of each type is not going to be easy.

Neuroanatomical Techniques and Directions

This module first describes a few of the most common neuroanatomical techniques. Then, it explains the system of directions that neuroanatomists use to describe the location of structures in vertebrate nervous systems.

Neuroanatomical Techniques

LO 3.7 Compare several neuroanatomical research techniques.

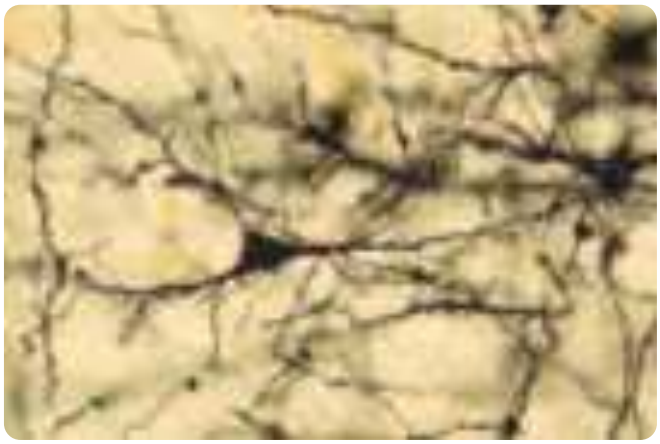
The major problem in visualizing neurons is not that they are minute. The major problem is that neurons are so tightly packed and their axons and dendrites so intricately intertwined that looking through a microscope at unprepared neural tissue reveals almost nothing about them. The key to the study of neuroanatomy lies in preparing neural tissue in a variety of ways, each of which permits a clear view of a different aspect of neuronal structure, and then combining the knowledge obtained from each of the preparations. This point is illustrated by the following widely used neuroanatomical techniques.

GOLGI STAIN. The greatest blessing to befall neuroscience in its early years was the accidental discovery of the **Golgi stain** by Camillo Golgi (pronounced "GOLE-jee"), an Italian physician, in the early 1870s. Golgi was trying to stain the meninges, by exposing a block of neural tissue to potassium dichromate and silver nitrate, when he noticed an amazing thing. For some unknown reason, the silver chromate created by the chemical reaction of the two substances Golgi was using invaded a few neurons in each slice of tissue and stained each invaded neuron entirely black. This discovery made it possible to see individual neurons for the first time, although only in silhouette (see Figure 3.11). Golgi stains are commonly used to discover the overall shape of neurons.

NISSL STAIN. Although the Golgi stain permits an excellent view of the silhouettes of the few neurons that take up the stain, it provides no indication of the number of neurons in an area. The first neural staining procedure to overcome this shortcoming was the **Nissl stain**, which was developed by Franz Nissl, a German psychiatrist, in the 1880s. The most common dye used in the Nissl method is cresyl violet. Cresyl violet and other Nissl dyes penetrate all cells on a slide, but they bind to molecules (i.e., DNA and RNA) that are most prevalent in neuron cell bodies. Thus, they often are used to estimate the number of cell bodies in an area, by counting the number of Nissl-stained dots. Figure 3.12 is a photograph of a slice of brain tissue stained with cresyl violet. Notice that only the layers composed mainly of neuron cell bodies are densely stained.

ELECTRON MICROSCOPY. A neuroanatomical technique that provides information about the details of neuronal structure is **electron microscopy** (pronounced "my-CROSS-cuh-pee"). Because of the nature of light, the limit of magnification in light microscopy is about 1,500 times, a level of magnification insufficient to reveal

Figure 3.11 Neural tissue that has been stained by the Golgi method. Because only a few neurons take up the stain, their silhouettes are revealed in great detail, but their internal details are invisible.



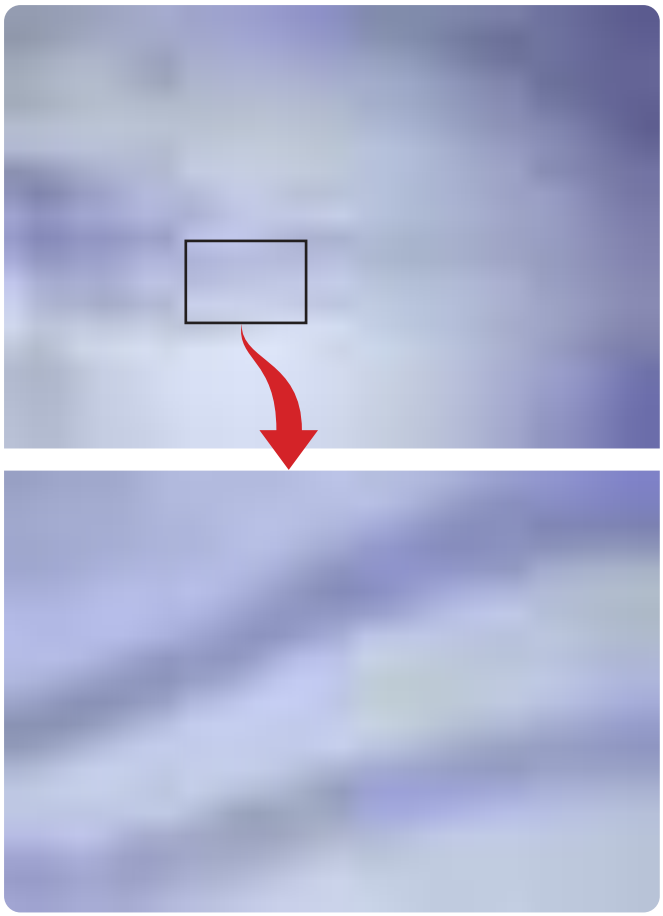
Martin M. Rotker/Science Source

the fine anatomical details of neurons. Greater detail can be obtained by first coating thin slices of neural tissue with an electron-absorbing substance that is taken up by different parts of neurons to different degrees, then passing a beam of electrons through the tissue onto a photographic film. The result is an *electron micrograph*, which captures neuronal structure in exquisite detail. A *scanning electron microscope* provides spectacular electron micrographs in three dimensions (see Figure 3.13), but it is not capable of as much magnification as conventional electron microscopy. The strength of electron microscopy is also a weakness: Because the images are so detailed, they can make it difficult to visualize general aspects of neuroanatomical structure.

NEUROANATOMICAL TRACING TECHNIQUES. Neuroanatomical tracing techniques are of two types: anterograde (forward) tracing methods and retrograde (backward) tracing methods (see Figure 3.14). *Anterograde tracing methods* are used when an investigator wants to trace the paths of axons projecting away from cell bodies located in a particular area. The investigator begins by injecting one of several chemicals commonly used for anterograde tracing into the cell body. It is then taken up by cell bodies and transported forward along their axons to their terminal buttons. Then, after a few days, the investigator removes the brain and slices it. Those slices are then treated to reveal the locations of the injected chemical.

Retrograde tracing methods work in the reverse manner; they are used when an investigator wants to trace the paths of axons projecting into a particular area. The investigator begins by injecting one of several chemicals commonly used for retrograde-tracing into an area of the brain. These chemicals are taken up by terminal buttons and then transported

Figure 3.12 The Nissl stain. Presented here is a Nissl-stained section through the rat hippocampus, at two levels of magnification to illustrate two uses of Nissl stains. Under low magnification (top panel), Nissl stains provide a gross indication of brain structure by selectively staining groups of neural cell bodies. Under higher magnification (bottom panel), one can distinguish individual neural cell bodies, and thus, count the number of neurons in various areas.



Carl Ernst/Brian Christie/University of British Columbia Department of Psychology

Figure 3.13 A color-enhanced scanning electron micrograph of a neuron cell body (green) studded with terminal buttons (orange). Each neuron receives numerous synaptic contacts.

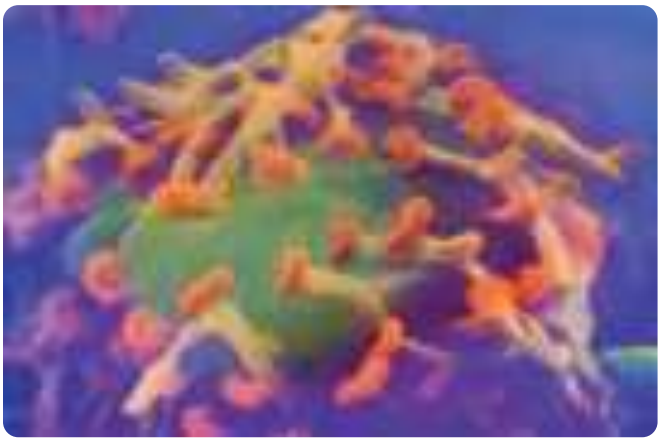
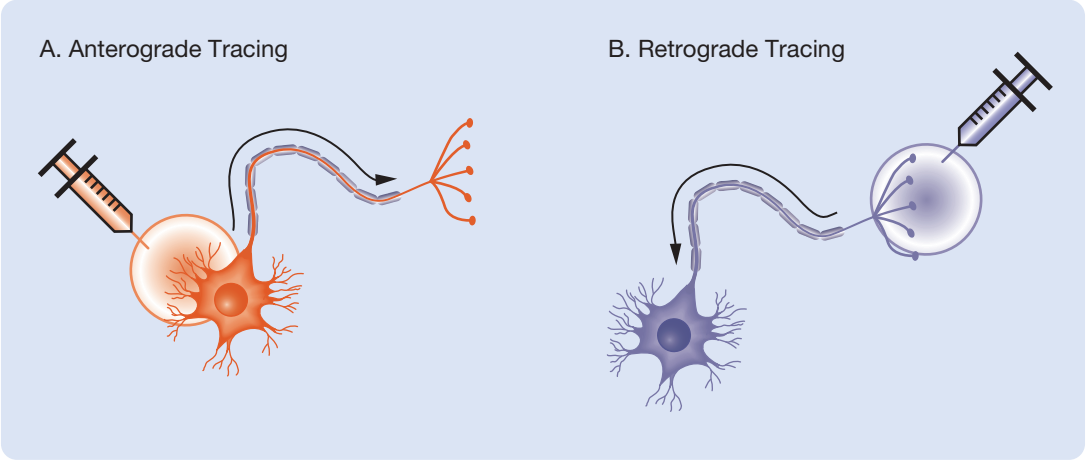


Photo Researchers/Science History Images/Alamy Stock Photo

Figure 3.14 One example of anterograde tracing (A) and one example of retrograde tracing (B).



backward along their axons to their cell bodies. After a few days, the investigator removes the brain and slices it. Those slices are then treated to reveal the locations of the injected chemical.

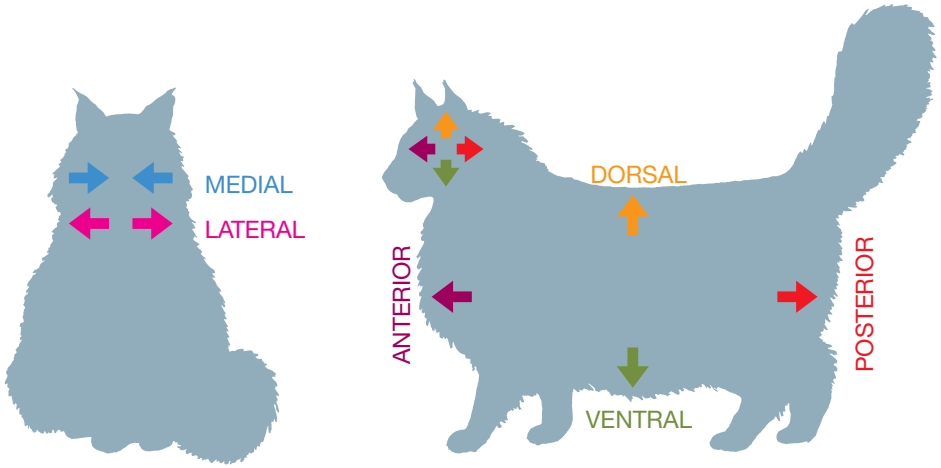
Directions in the Vertebrate Nervous System

LO 3.8 **Illustrate the neuroanatomical directions.**

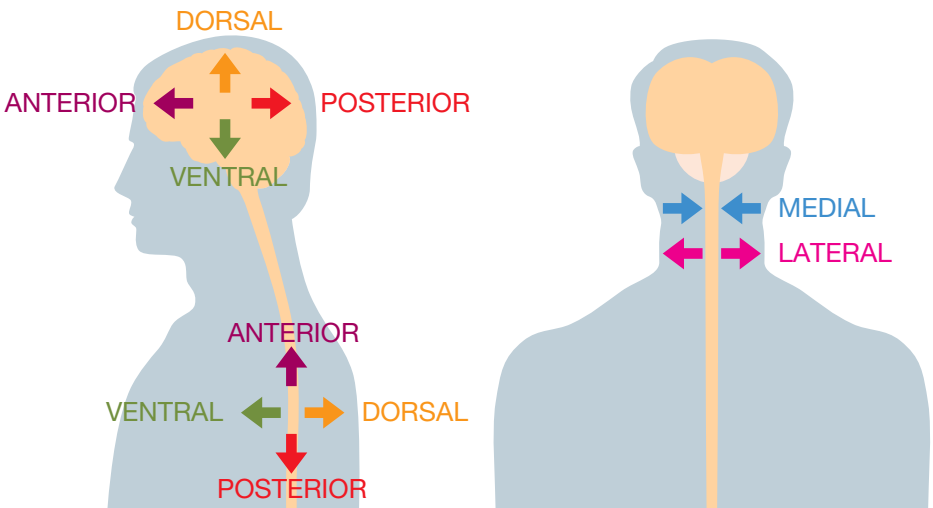
It would be difficult for you to develop an understanding of the layout of an unfamiliar city without a system of directional coordinates: north–south, east–west. The same goes for the nervous system. Thus, before introducing you to the locations of major nervous system structures, we will describe the three-dimensional system of directional coordinates used by neuroanatomists.

Directions in the vertebrate nervous system are described in relation to the orientation of the spinal cord. This system is straightforward for most vertebrates, as Figure 3.15a indicates. The vertebrate nervous system has three axes: anterior–posterior, dorsal–ventral, and medial–lateral. First,

Figure 3.15 (a) Anatomical directions in representative vertebrates, my (JP) cats Sambala and Rastaman. (b) Anatomical directions in a human. Notice that the directions in the cerebral hemispheres are rotated by 90° in comparison to those in the spinal cord and brain stem because of the unusual upright posture of humans.



(a)



(b)

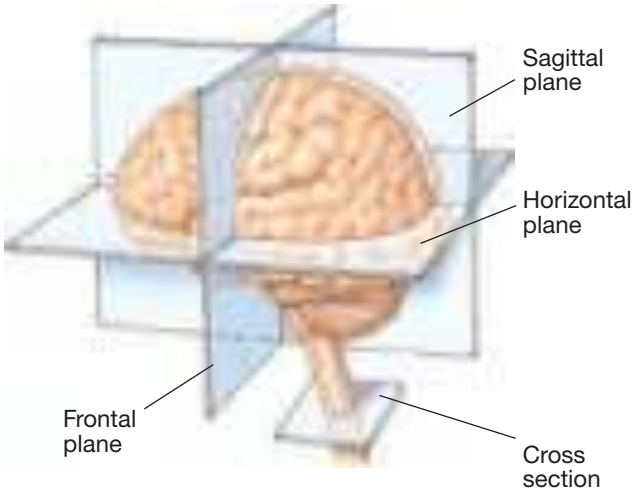
anterior means toward the nose end (the anterior end), and **posterior** means toward the tail end (the posterior end); these same directions are sometimes referred to as *rostral* and *caudal*, respectively. Second, **dorsal** means toward the surface of the back or the top of the head (the dorsal surface), and **ventral** means toward the surface of the chest or the bottom of the head (the ventral surface). Third, **medial** means toward the midline of the body, and **lateral** means away from the midline toward the body's lateral surfaces.

Humans complicate this simple three-axis (anterior–posterior, ventral–dorsal, medial–lateral) system of neuroanatomical directions by insisting on walking around on our hind legs. This changes the orientation of our cerebral hemispheres in relation to our spines and brain stems.

You can save yourself a lot of confusion if you remember that the system of vertebrate neuroanatomical directions was adapted for use in humans in such a way that the terms used to describe the positions of various body surfaces are the same in humans as they are in more typical, non-upright vertebrates. Specifically, notice that the top of the human head and the back of the human body are both referred to as *dorsal* even though they are in different directions, and the bottom of the human head and the front of the human body are both referred to as *ventral* even though they are in different directions (see Figure 3.15b). To circumvent this complication, the terms **superior** and **inferior** are often used to refer to the top and bottom of the primate head, respectively.

Proximal and *distal* are two other common directional terms. In general, **proximal** means "close," and **distal** means "far." Specifically, with regard to the peripheral nervous system, *proximal* means closer to the CNS, and *distal* means farther from the CNS. Your shoulders are proximal to your elbows, and your elbows are proximal to your fingers.

Figure 3.16 Horizontal, frontal (coronal), and sagittal planes in the human brain and a cross section of the human spinal cord.



In the next module, you will see drawings of sections (slices) of the brain cut in one of three different planes: **horizontal sections**, **frontal sections** (also termed *coronal sections*), and **sagittal sections**. These three planes are illustrated in Figure 3.16. A section cut down the center of the brain, between the two hemispheres, is called a *midsagittal section*. A section cut at a right angle to any long, narrow structure, such as the spinal cord or a nerve, is called a **cross section**.

Scan Your Brain

This is a good place for you to pause to scan your brain. Are you ready to proceed to the structures of the brain and spinal cord? Test your grasp of the preceding modules of this chapter by drawing a line between each term in the left column and the appropriate word or phrase in the right column. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. myelin	**8.** synaptic vesicles	**a.** gaps	**h.** protein synthesis
2. soma	**9.** astrocytes	**b.** cone-shaped region	**i.** the forgotten cells
3. axon hillock	**10.** ganglia	**c.** packaging membranes	**j.** CNS myelinators
4. Golgi complex	**11.** oligodendrocytes	**d.** fatty substance	**k.** black
5. ribosomes	**12.** Golgi stain	**e.** neurotransmitter storage	**l.** largest glial cells
6. synapses	**13.** dorsal	**f.** cell body	**m.** caudal
7. glial cells	**14.** posterior	**g.** PNS clusters of cell bodies	**n.** top of head

Scan Your Brain answers: (1) d, (2) f, (3) b, (4) c, (5) h, (6) a, (7) i, (8) e, (9) l, (10) g, (11) j, (12) k, (13) n, (14) m.

Anatomy of the Central Nervous System

In the first three modules of this chapter, you learned about the divisions of the nervous system, the cells that compose it, and some of the neuroanatomical techniques used to study it. This final module focuses exclusively on the anatomy of the CNS. Your ascent through the CNS will begin with a focus on the spinal cord, and then you will move up to the brain.

Spinal Cord

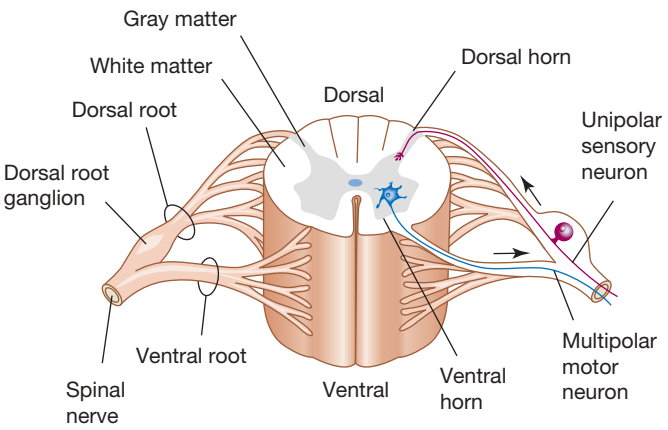
LO 3.9 Draw and label a cross section of the spinal cord.

In cross section, it is apparent that the spinal cord comprises two different areas (see Figure 3.17): an inner H-shaped core of gray matter and a surrounding area of white matter. **Gray matter** is composed largely of cell bodies and unmyelinated interneurons, whereas **white matter** is composed largely of myelinated axons. (It is the myelin that gives the white matter its glossy white sheen.) The two dorsal arms of the spinal gray matter are called the **dorsal horns**, and the two ventral arms are called the **ventral horns**.

Pairs of *spinal nerves* are attached to the spinal cord—one on the left and one on the right—at 31 different levels of the spine. Each of these 62 spinal nerves divides as it nears the cord (see Figure 3.17), and its axons are joined to the cord via one of two roots: the *dorsal root* or the *ventral root*.

All dorsal root axons, whether somatic or autonomic, are sensory (afferent) unipolar neurons with their cell bodies grouped together just outside the cord to form the **dorsal root ganglia** (see Figure 3.17). As you can see, many of their synaptic terminals are in the dorsal horns of the spinal gray matter. In contrast, the neurons of the ventral root are motor (efferent) multipolar neurons with their cell bodies in the ventral horns. Those that are part of the somatic nervous system project to skeletal muscles; those that are part of the autonomic nervous system project to ganglia, where they synapse on neurons that in turn project to internal organs (heart, stomach, liver, etc.). See Appendix I.

Figure 3.17 A schematic cross section of the spinal cord, and the dorsal and ventral roots.



Five Major Divisions of the Brain

LO 3.10 List and discuss the five major divisions of the human brain.

A necessary step in learning to live in an unfamiliar city is learning the names and locations of its major neighborhoods or districts. Those who possess this information can easily communicate the general location of any destination in the city. This section of the chapter introduces you to the five "neighborhoods," or divisions, of the brain—for much the same reason.

To understand why the brain is considered to be composed of five divisions, it is necessary to understand its early development. In the vertebrate embryo, the tissue that eventually develops into the CNS is recognizable as a fluid-filled tube (see Figure 3.18). The first indications of the developing brain are three swellings that occur at the anterior end of this tube. These three swellings eventually develop into the adult *forebrain*, *midbrain*, and *hindbrain*.

Before birth, the initial three swellings in the neural tube become five (see Figure 3.18). This occurs because the forebrain swelling grows into two different swellings, and so does the hindbrain swelling. From anterior to posterior, the five swellings that compose the developing brain at birth are the *telencephalon*, the *diencephalon*, the *mesencephalon* (or midbrain), the *metencephalon*, and the *myelencephalon* (*encephalon* means "within the head"). These swellings ultimately develop into the five divisions of the adult brain. As students, we memorized their order by remembering that the *t*elencephalon is on the *t*op and the other four divisions are arrayed below it in alphabetical order.

Figure 3.19 illustrates the locations of the telencephalon, diencephalon, mesencephalon, metencephalon, and myelencephalon in the adult human brain. Notice that in humans, as in other higher vertebrates, the telencephalon (the left and right *cerebral hemispheres*) undergoes the greatest growth during development. The other four divisions of the brain are often referred to collectively as the **brain stem**—the stem on which the cerebral hemispheres sit. The myelencephalon is often referred to as the *medulla*.

Figure 3.18 The early development of the mammalian brain illustrated in schematic horizontal sections. Compare with the adult human brain in Figure 3.19.

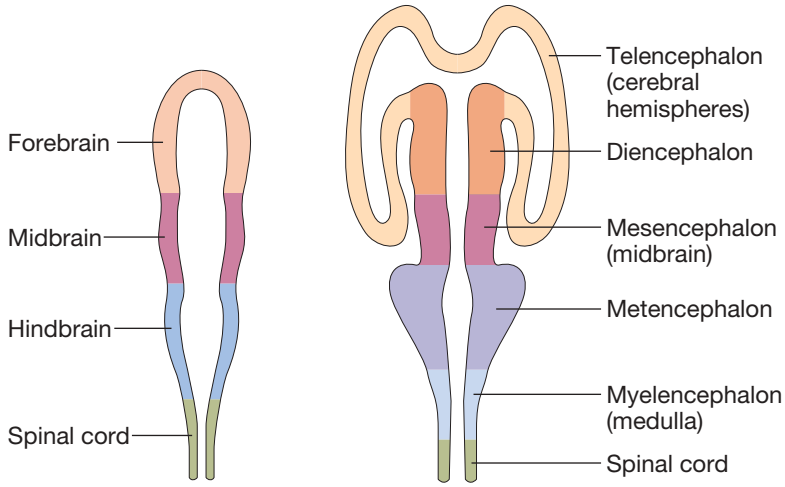
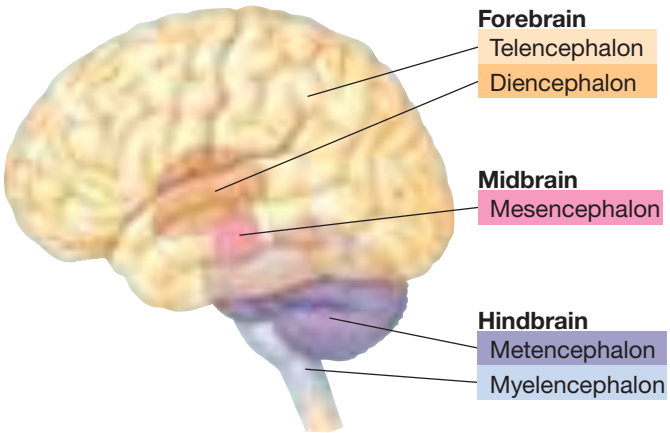


Figure 3.19 The five divisions of the adult human brain.



Now that you have learned the five major divisions of the brain, it is time to introduce you to their major structures. We begin our survey of brain structures in the myelencephalon, then ascend through the other divisions to the telencephalon.

Myelencephalon

LO 3.11 List and describe the components of the myelencephalon.

Not surprisingly, the **myelencephalon (**or **medulla)**, the most posterior division of the brain, is composed largely of tracts carrying signals between the rest of the brain and the body. An interesting part of the myelencephalon from a psychological perspective is the **reticular formation** (see Figure 3.20). It is a complex network of about 100 tiny nuclei that occupies the central core of the brain stem from the posterior boundary of the myelencephalon to the anterior boundary of the midbrain. It is so named because of its netlike appearance (*reticulum* means "little net"). Sometimes, the reticular formation is referred to as the *reticular activating system* because parts of it seem to play a role in arousal. However, the various nuclei of the reticular formation are involved in a variety of functions—including sleep, attention, movement, the maintenance of muscle tone, and various cardiac, circulatory, and respiratory reflexes. Accordingly, referring to this collection of nuclei as a *system* can be misleading.

Metencephalon

LO 3.12 List and describe the components of the metencephalon.

The **metencephalon**, like the myelencephalon, houses many ascending and descending tracts and part of the reticular formation. These structures create a bulge, called the **pons**, on the brain stem's ventral surface. The pons is one major division of the metencephalon; the other is the cerebellum (little brain)—see Figure 3.21. The **cerebellum** is the large, convoluted structure on the brain stem's dorsal surface. It is an important sensorimotor structure; cerebellar damage eliminates the ability to precisely control one's movements and to adapt them to changing conditions. However, the fact that cerebellar damage also produces a variety of cognitive deficits (e.g., deficits in decision making and in the use of language) suggests that the functions of the cerebellum are not restricted to sensorimotor control.

Figure 3.20 Structures of the human myelencephalon (medulla) and metencephalon.

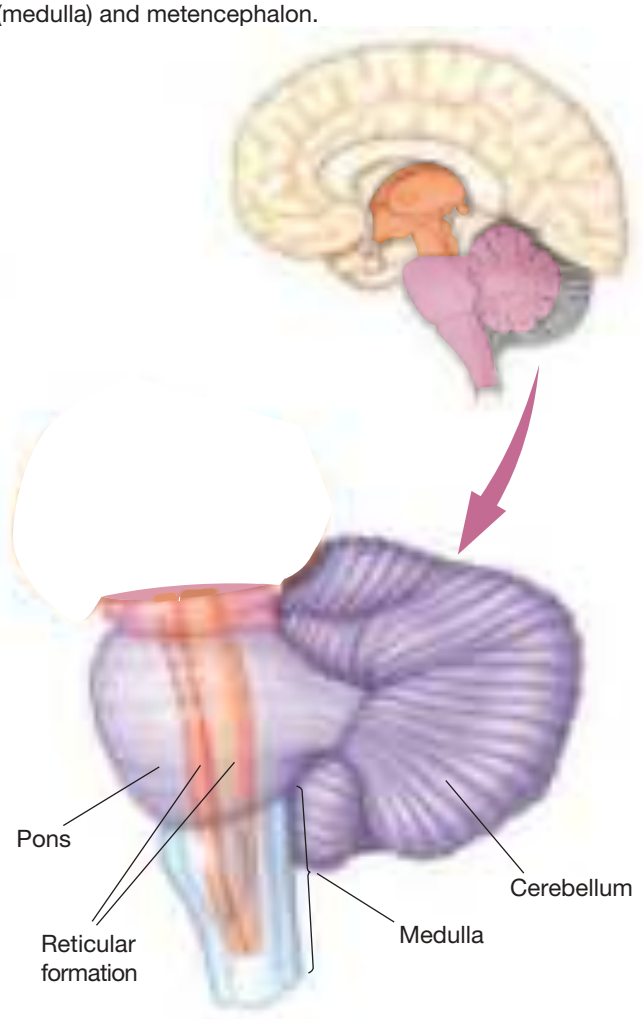
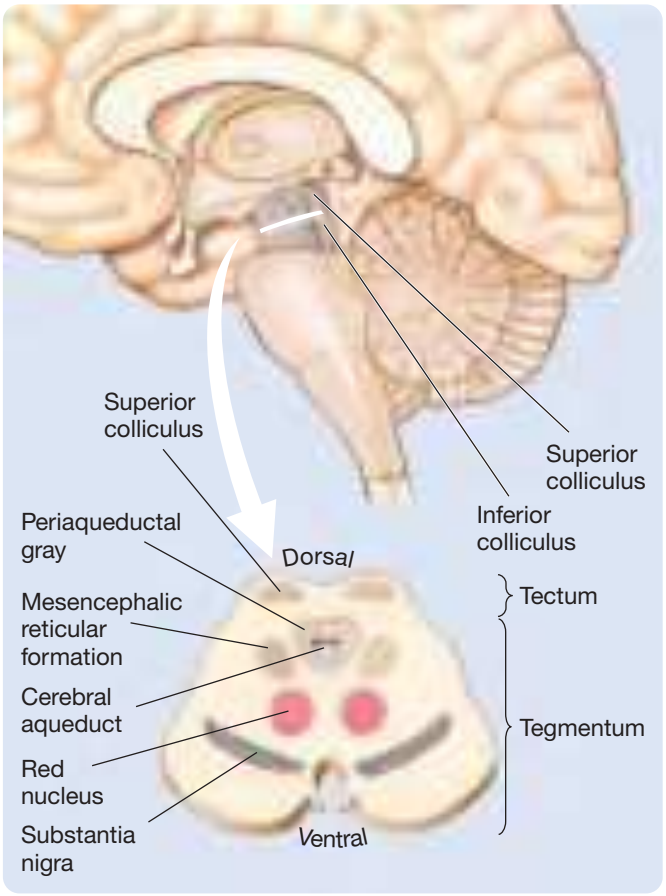


Figure 3.21 The human mesencephalon (midbrain).



Mesencephalon

LO 3.13 List and describe the components of the mesencephalon.

The **mesencephalon**, like the metencephalon, has two divisions. The two divisions of the mesencephalon are the tectum and the tegmentum (see Figure 3.21). The **tectum** (roof) is the dorsal surface of the midbrain. In mammals, the tectum is composed of two pairs of bumps, the *colliculi* (little hills). The posterior pair, called the **inferior colliculi**, have an auditory function. The anterior pair, called the **superior colliculi**, have a visual-motor function; more specifically, to direct the body's orientation toward or away from particular visual stimuli (see Gandhi & Katnani, 2011). In lower vertebrates, the function of the tectum is entirely visual-motor, and it is sometimes referred to as the *optic tectum*.

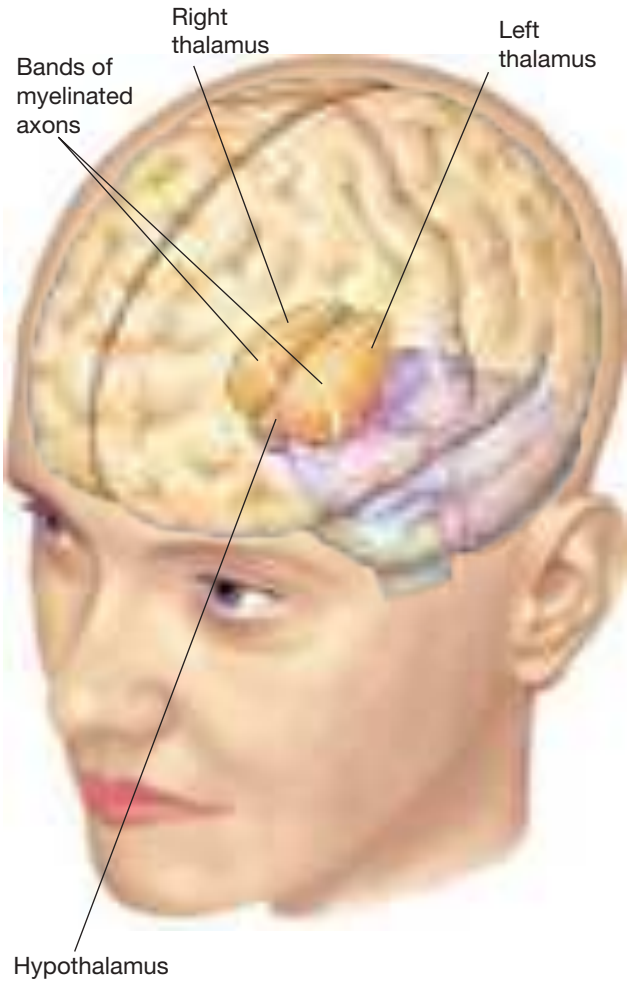
The **tegmentum** is the division of the mesencephalon ventral to the tectum. In addition to the reticular formation and tracts of passage, the tegmentum contains three colorful structures of particular interest to biopsychologists: the periaqueductal gray, the substantia nigra, and the red nucleus (see Figure 3.21). The **periaqueductal gray** is the gray matter situated around the **cerebral aqueduct**, the duct connecting the third and fourth ventricles; it is of special interest because of its role in mediating the analgesic (pain-reducing) effects of opioid drugs. The **substantia nigra** (black substance) and the **red nucleus** are both important components of the sensorimotor system.

Diencephalon

LO 3.14 List and describe the components of the diencephalon.

The **diencephalon** is composed of two structures: the thalamus and the hypothalamus (see Figure 3.22). The **thalamus** is the large, two-lobed structure that constitutes the top of the brain stem. One lobe sits on each side of the third ventricle, and the two lobes are joined by the **massa intermedia**, which runs through the ventricle. Visible on the surface of the thalamus are white *lamina* (layers) that are composed of myelinated axons.

Figure 3.22 The human diencephalon.



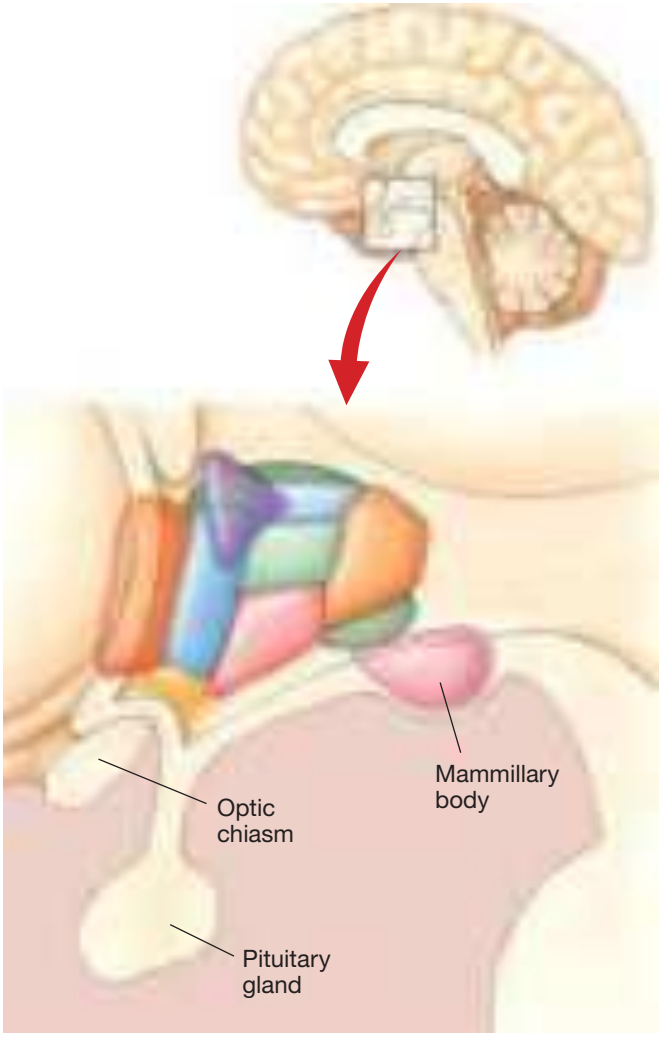
The thalamus comprises many different pairs of nuclei, most of which project to the cortex. The general organization of the thalamus is illustrated in Appendix V.

The most well-understood thalamic nuclei are the **sensory relay nuclei**—nuclei that receive signals from sensory receptors, process them, and then transmit them to the appropriate areas of sensory cortex. For example, the **lateral geniculate nuclei**, the **medial geniculate nuclei**, and the **ventral posterior nuclei** are important relay stations in the visual, auditory, and somatosensory systems, respectively. Sensory relay nuclei are not one-way streets; they all receive feedback signals from the very areas of cortex to which they project (Zembrzycki et al., 2013). Although less is known about the other thalamic nuclei, the majority of them receive input from areas of the cortex and project to other areas of the cortex (see Sherman, 2007).

The **hypothalamus** is located just below the anterior thalamus (*hypo* means "below")—see Figure 3.23. It plays an important role in the regulation of several motivated behaviors (e.g., eating, sleep, and sexual behavior). It exerts its effects in part by regulating the release of hormones from the **pituitary gland**, which dangles from it on the ventral surface of the brain. The literal meaning of *pituitary gland* is "snot gland"; it was first discovered in a gelatinous state behind the nose of a cadaver and was incorrectly assumed to be the main source of nasal mucus.

In addition to the pituitary gland, two other structures appear on the inferior surface of the hypothalamus: the optic chiasm and the mammillary bodies (see Figure 3.23). The **optic chiasm** is the point at which the *optic nerves* from each eye come together and then **decussate** (cross over to the other side of the brain) (see Chapter 6). The decussating fibers are said to be **contralateral** (projecting from one side of the body to the other), and the nondecussating fibers are said to be **ipsilateral** (staying on the same side of the body). The **mammillary bodies**,

Figure 3.23 The human hypothalamus (in color) in relation to the optic chiasm and the pituitary gland.



which are often considered to be part of the hypothalamus, are a pair of spherical nuclei located on the inferior surface of the hypothalamus, just behind the pituitary. The mammillary bodies and the other nuclei of the hypothalamus are illustrated in Appendix VI.

Telencephalon

LO 3.15 List and describe the components of the telencephalon.

The **telencephalon**, the largest division of the human brain, mediates the brain's most complex functions. It initiates voluntary movement, interprets sensory input, and mediates complex cognitive processes such as learning, speaking, and problem solving.

CEREBRAL CORTEX. The cerebral hemispheres are covered by a layer of tissue called the **cerebral cortex** (cerebral bark). Because the cerebral cortex is mainly composed of small, unmyelinated neurons, it is gray and is often referred to as the *gray matter*. In contrast, the layer beneath the cortex is mainly composed of large myelinated axons, which are white and often referred to as the *white matter*.

In humans, the cerebral cortex is deeply convoluted (furrowed)—see Figure 3.24. The *convolutions* have the effect of increasing the amount of cerebral cortex without increasing the overall volume of the brain. Not all mammals have convoluted cortexes; most mammals are *lissencephalic* (smooth-brained).

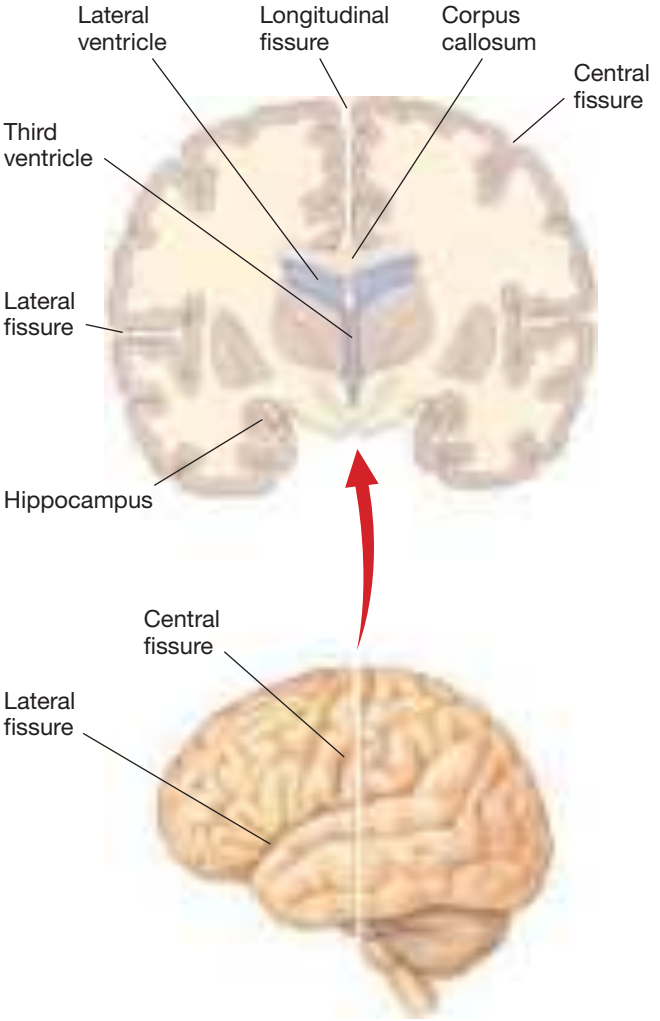
It was once believed that the number and size of cortical convolutions determined a species' intellectual capacities; however, the number and size of cortical convolutions appear to be related more to body size. Every large mammal has an extremely convoluted cortex.

Journal Prompt 3.2

Why do you think only large mammals have extremely convoluted cortices?

The large furrows in a convoluted cortex are called **fissures**, and the small ones are called **sulci** (singular *sulcus*). The ridges between fissures and sulci are called **gyri** (singular *gyrus*). It is apparent in Figure 3.24 that the cerebral hemispheres are almost completely separated by the largest of the fissures: the **longitudinal fissure**. The cerebral hemispheres are directly connected by a few tracts spanning the longitudinal fissure; these

Figure 3.24 The major fissures of the human cerebral cortex.

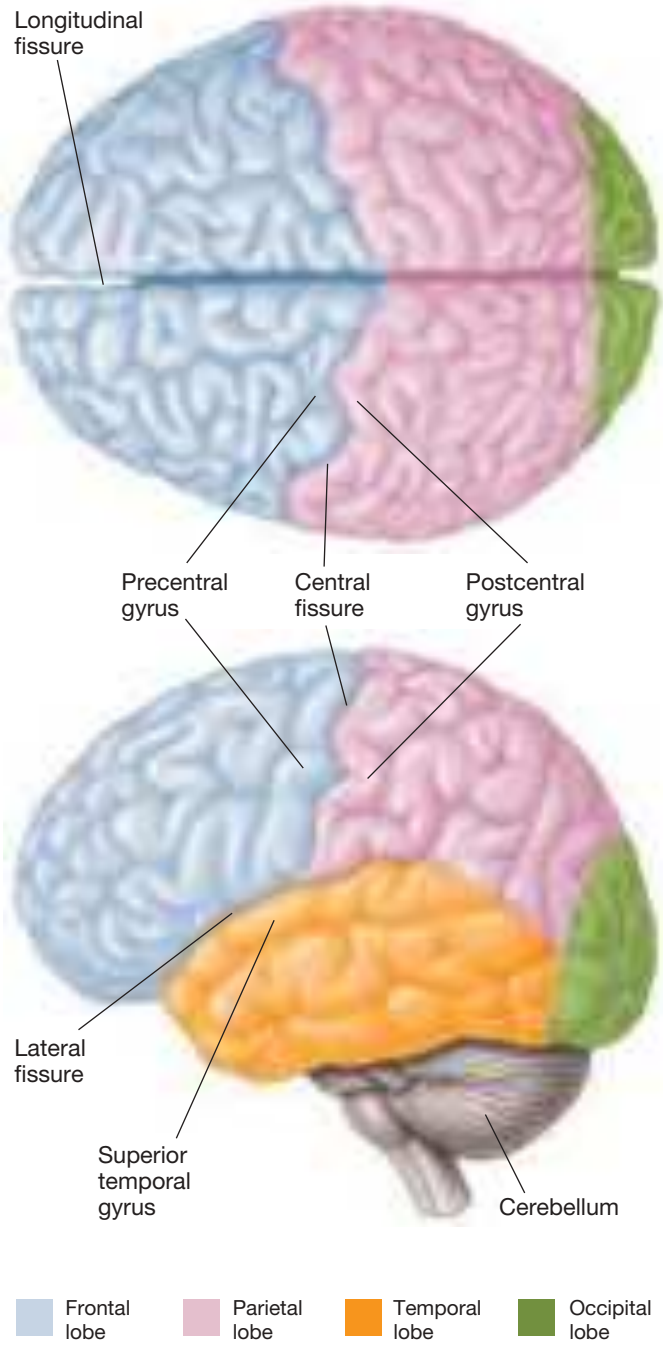


hemisphere-connecting tracts are called **cerebral commissures**. The largest cerebral commissure, the **corpus callosum**, is clearly visible in Figure 3.24.

As Figures 3.24 and 3.25 indicate, the two major landmarks on the lateral surface of each hemisphere are the **central fissure** and the **lateral fissure**. These fissures partially divide each hemisphere into four lobes: the **frontal lobe**, the **parietal lobe** (pronounced "pa-RYE-e-tal"), the **temporal lobe**, and the **occipital lobe** (pronounced "ok-SIP-i-tal"). Among the largest gyri are the **precentral gyri**, the **postcentral gyri**, and the **superior temporal gyri** in the frontal, parietal, and temporal lobes, respectively.

It is important to understand that the cerebral lobes are not functional units. It is best to think of the cerebral cortex as a flat sheet of cells that just happens to be divided into lobes because it folds in on itself at certain places during development. Thus, it is incorrect to think that a lobe is a functional unit, having one set of functions.

Figure 3.25 The lobes of the cerebral hemisphere.



Still, it is useful at this early stage of your biopsychological education to get a general idea of various functions of areas within each lobe. More thorough discussions of the cerebral localization of brain functions are presented in later chapters.

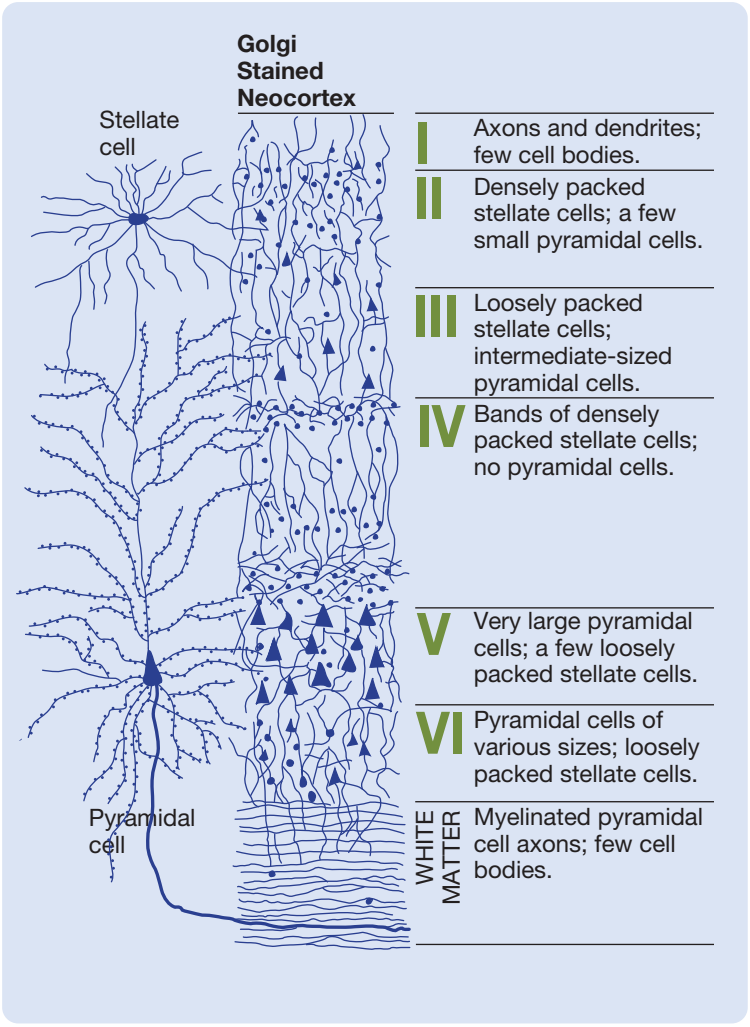
The main function of the occipital lobes is quite straightforward: We humans rely heavily on the analysis of visual input to guide our behavior, and the occipital cortex and large areas of adjacent cortex perform this function. There are two large functional areas in each parietal lobe: The postcentral gyrus analyzes sensations from the body (e.g., touch), whereas the remaining areas of cortex in the posterior parts of the parietal lobes play roles in perceiving the location of both objects and our own bodies and in directing our attention. The cortex of each temporal lobe has three general functional areas: The superior temporal gyrus is involved in hearing and language, the inferior temporal cortex identifies complex visual patterns, and the medial portion of temporal cortex (which is not visible from the usual side view) is important for certain kinds of memory. Lastly, each frontal lobe has two distinct functional areas: The precentral gyrus and adjacent frontal cortex have a motor function, whereas the frontal cortex anterior to motor cortex performs complex cognitive functions, such as planning response sequences, evaluating the outcomes of potential patterns of behavior, and assessing the significance of the behavior of others (see Euston, Gruber, & McNaughton, 2012; Isoda & Noritake, 2013; Pezzulo et al., 2014).

About 90 percent of human cerebral cortex is **neocortex** (new cortex), also known as *isocortex*. By convention, the layers of neocortex are numbered I through VI, starting at the surface. Figure 3.26 illustrates two adjacent sections of neocortex. One has been stained with a Nissl stain to reveal the number and shape of its cell bodies; the other has been stained with a Golgi stain to reveal the silhouettes of a small proportion of its neurons.

Three important characteristics of neocortical anatomy are apparent from the sections in Figure 3.26. First, it is apparent that many cortical neurons fall into one of two different categories: pyramidal (pyramid-shaped) cells and stellate (star-shaped) cells. **Pyramidal cells** are large multipolar neurons with pyramid-shaped cell bodies, a large dendrite called an *apical dendrite* that extends from the apex of the pyramid straight toward the cortex surface, and a very long axon (see Lodato, Shetty, & Arlotta, 2015). In contrast, **stellate cells** are small star-shaped interneurons (neurons with a short axon or no axon). Second, it is apparent that the six layers of neocortex differ from one another in terms of the size and density of their cell bodies and the relative proportion of pyramidal and stellate cell bodies that they contain. Third, it is apparent that many long axons and dendrites course vertically (i.e., at right angles to the cortical layers) through the neocortex. This vertical flow of information is the basis of the neocortex's **columnar organization**: Neurons in a given vertical column of neocortex often form a mini-circuit that performs a single function (see Rowland & Moser, 2014).

A fourth important characteristic of neocortical anatomy is not apparent in Figure 3.26: Although neocortex is six-layered, there are variations in the thickness of the respective layers from area to area (see Zilles & Amunts,

Figure 3.26 The six layers of neocortex. The thickness of the cell layers can give a clue as to the function of an area of neocortex. For example, the thickness of layer IV indicates that this is sensory neocortex.



Based on Rakic, P. (1979)

2010). For example, because the stellate cells of layer IV are specialized for receiving sensory signals from the thalamus, layer IV is extremely thick in areas of sensory cortex. Conversely, because the pyramidal cells of layer V conduct signals from the neocortex to the brain stem and spinal cord, layer V is extremely thick in areas of motor cortex.

The **hippocampus** is one important area of cortex that is not neocortex—it has only three major layers (see Schultz & Engelhardt, 2014). The hippocampus is located at the medial edge of the cerebral cortex as it folds back on itself in the medial temporal lobe (see Figure 3.24). This folding produces a shape that is, in cross section, somewhat reminiscent of a seahorse (*hippocampus* means "sea horse"). The hippocampus plays a major role in some kinds of memory (see Chapter 11).

Limbic System and the Basal Ganglia

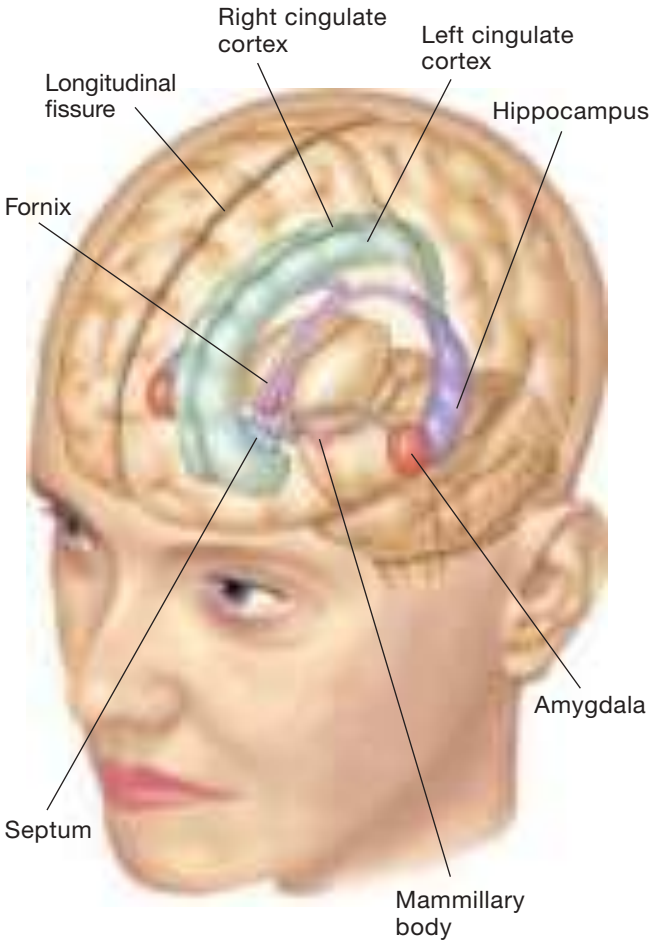
LO 3.16 List and describe the components of the limbic system and of the basal ganglia.

Although much of the subcortical portion of the telencephalon is taken up by axons projecting to and from the neocortex, there are several large subcortical nuclear groups. Some of them are considered part of either the *limbic system* or the *basal ganglia system*. Don't be misled by the word *system* in these contexts; it implies a level of certainty that is unwarranted. It is not entirely clear exactly what these hypothetical systems do, exactly which structures should be included in them, or even whether it is appropriate to view them as unitary systems. Nevertheless, if not taken too literally, the concepts of *limbic system* and *basal ganglia system* provide a useful means of conceptualizing the organization of several subcortical structures.

The **limbic system** is a circuit of midline structures that circle the thalamus (*limbic* means "ring"). The limbic system is involved in the regulation of motivated behaviors—including the four F's of motivation: fleeing, feeding, fighting, and sexual behavior. (This joke is as old as biopsychology itself, but it is a good one.) In addition to the structures about which you have already read (the mammillary bodies and the hippocampus), major structures of the limbic system include the amygdala, the fornix, the cingulate cortex, and the septum.

Let's begin tracing the limbic circuit (see Figure 3.27) at the **amygdala**—the almond-shaped nucleus in the anterior temporal lobe (*amygdala* means "almond" and is pronounced "a-MIG-dah-lah"). Posterior to the amygdala is the hippocampus, which runs beneath the thalamus in the medial temporal lobe. Next in the ring are the cingulate cortex and the fornix. The **cingulate cortex** is the large strip of cortex in the **cingulate gyrus** on the medial surface of the cerebral hemispheres, just superior to the corpus callosum; it encircles the dorsal thalamus (*cingulate* means "encircling"). The **fornix**, the major tract of the limbic system, also encircles the dorsal thalamus; it leaves the dorsal end of the hippocampus and sweeps forward in an arc coursing along the superior surface of the third ventricle and terminating in the septum and the mammillary bodies (*fornix* means "arc"). The **septum** is a midline nucleus located at the anterior tip of the cingulate cortex. Several tracts connect the septum and mammillary

Figure 3.27 The major structures of the limbic system: amygdala, hippocampus, cingulate cortex, fornix, septum, and mammillary body.



bodies with the amygdala and hippocampus, thereby completing the limbic ring.

The functions of the hippocampus, the hypothalamus and the amygdala have been investigated more than those of the other limbic structures. As stated previously, the hippocampus plays a role in certain forms of memory, and the hypothalamus is involved in a variety of motivated behaviors such as eating, sleep, and sexual behavior. The amygdala, on the other hand, is involved in emotion—particularly fear. You will learn much more about these structures in later chapters.

The **basal ganglia** are illustrated in Figure 3.28. The long tail-like **caudate** (*caudate* means "tail-like") and **putamen** (pronounced "pew-TAY-men") receive inputs from the neocortex (see Graybiel, 2000). Together, the caudate and putamen, which both have a striped appearance, are known as the **striatum** (striped structure). The striatum's major output is to a pale circular structure known as the **globus pallidus** (pale globe). The globus pallidus is located medial to the putamen between the putamen and the thalamus.

The basal ganglia play a role in the performance of voluntary motor responses and decision making (see Hikosaka et al., 2014). Of particular interest is a pathway that projects to the striatum from the substantia nigra of the midbrain: *Parkinson's disease*, a disorder characterized by rigidity, tremors, and poverty of voluntary movement, is associated with the deterioration of this pathway. Another part of the basal ganglia that is of particular interest to biopsychologists is the *nucleus accumbens*, which is in the medial portion of the ventral striatum (see Figure 3.28). The nucleus accumbens is thought to play a role in the rewarding effects of addictive drugs and other reinforcers.

Figure 3.29 summarizes the major brain divisions and structures whose names have appeared in boldface in this section

Figure 3.28 The basal ganglia: striatum (caudate plus putamen), and globus pallidus. Notice that, in this view, the right globus pallidus is largely hidden behind the right thalamus and the left globus pallidus is totally hidden behind the left putamen.

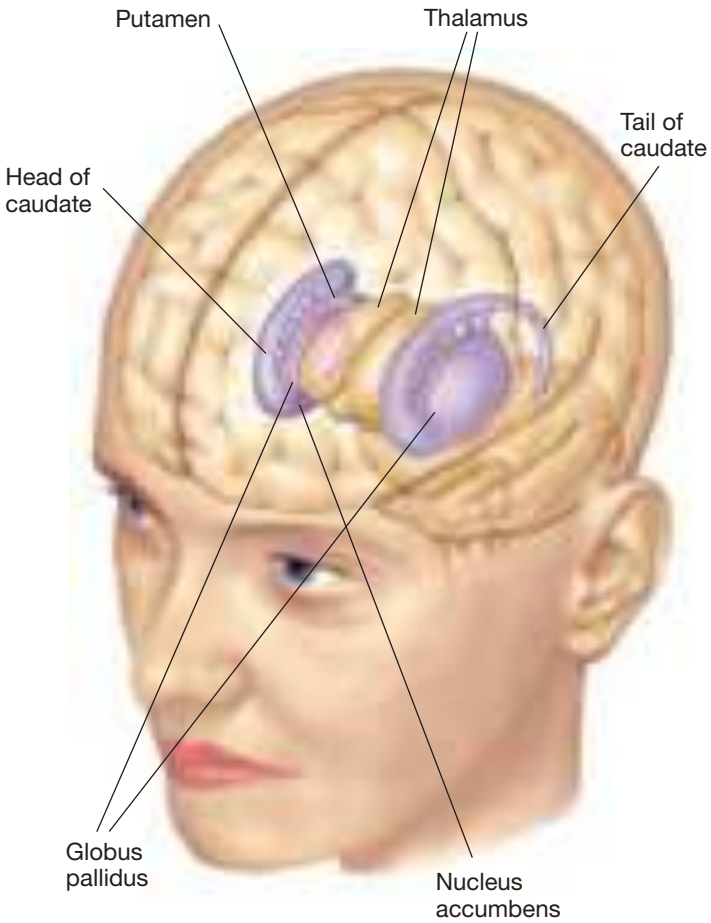
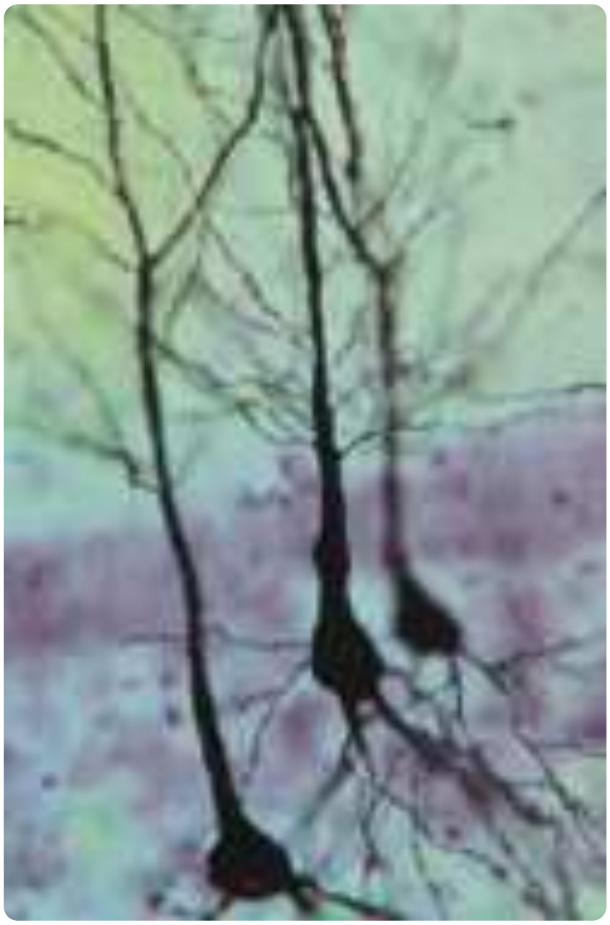


Figure 3.30 concludes this chapter, for reasons that too often get lost in the shuffle of neuroanatomical terms and technology. We have included it here to illustrate the beauty of the brain and the art of those who study its structure. We hope you are inspired by it. We wonder what thoughts its neural circuits once contained.

Figure 3.29 Summary of major brain structures.

Telencephalon	Cerebral cortex	Neocortex Hippocampus
	Major fissures	Central fissure Lateral fissure Longitudinal fissure
	Major gyri	Precentral gyrus Postcentral gyrus Superior temporal gyrus Cingulate gyrus
	Four lobes	Frontal lobe Temporal lobe Parietal lobe Occipital lobe
	Limbic system	Amygdala Hippocampus Fornix Cingulate cortex Septum Mammillary bodies
	Basal ganglia	Caudate, Putamen } Striatum Globus pallidus
	Cerebral commissures	Corpus callosum
Diencephalon	Thalamus	Massa intermedia Lateral geniculate nuclei Medial geniculate nuclei Ventral posterior nuclei
	Hypothalamus	Mammillary bodies
	Optic chiasm	
	Pituitary gland	
Mesencephalon	Tectum	Superior colliculi Inferior colliculi
	Tegmentum	Reticular formation Cerebral aqueduct Periaqueductal gray Substantia nigra Red nucleus
Metencephalon	Reticular formation Pons Cerebellum	
Myelencephalon or Medulla	Reticular formation	

Figure 3.30 The art of neuroanatomical staining. This slide was stained with both a Golgi stain and a Nissl stain. Clearly visible on the Golgi-stained pyramidal neurons are the pyramid-shaped cell bodies, the large apical dendrites, and numerous dendritic spines. Less obvious here is the long, narrow axon that projects from each pyramidal cell body off the bottom of this slide.

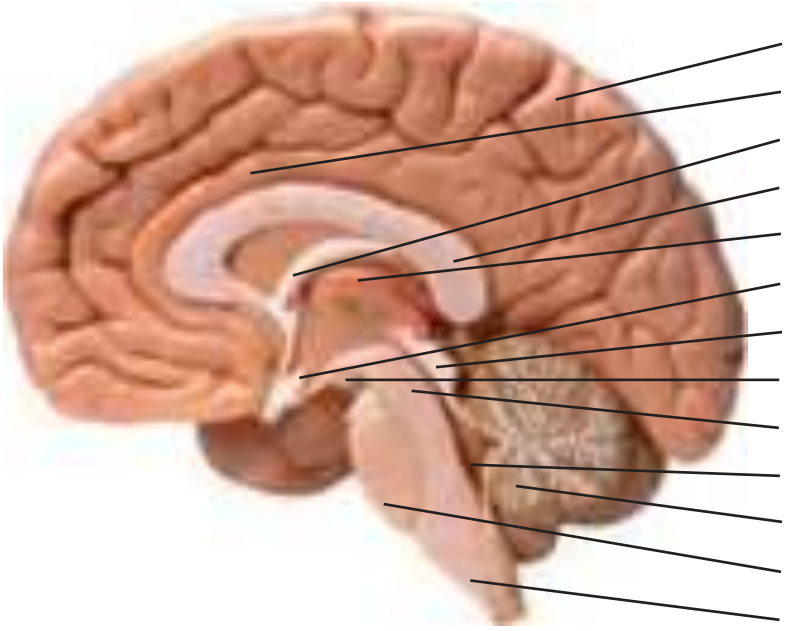


National Institute of Mental Health

Scan Your Brain

If you have not previously studied the gross anatomy of the brain, your own brain is probably straining under the burden of new terms. To determine whether you are ready to proceed, scan your brain by labeling the following midsagittal view of a real human brain. You may find it challenging to switch from color-coded diagrams to a photograph of a real brain.

The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions. Notice that Figure 3.29 includes all the brain anatomy terms that have appeared in bold type in this module and thus is an excellent review tool.



1. _____ lobe
2. _____ gyrus
3. _____
4. _____
5. _____
6. _____
7. _____ colliculus
8. _____ body
9. _____
10. _____ ventricle
11. _____
12. _____
13. _____

Mark Sykes/Alamy Stock Photo

Scan Your Brain answers: (1) parietal, (2) cingulate, (3) fornix, (4) corpus callosum, (5) thalamus, (6) hypothalamus, (7) inferior, (8) mammillary, (9) tegmentum, (10) fourth, (11) cerebellum, (12) pons, (13) medulla or myelencephalon.

Themes Revisited

This chapter contributed relatively little to the development of the text's themes. That development paused while you were being introduced to the key areas and structures of the human brain. A knowledge of fundamental neuroanatomy will serve as the foundation of discussions of brain function in subsequent chapters.

Key Terms

General Layout of the Nervous System
Central nervous system (CNS), p. 73
Peripheral nervous system (PNS), p. 73
Somatic nervous system (SNS), p. 73
Afferent nerves, p. 73
Efferent nerves, p. 73
Autonomic nervous system (ANS), p. 73
Sympathetic nerves, p. 74
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Pia mater, p. 75
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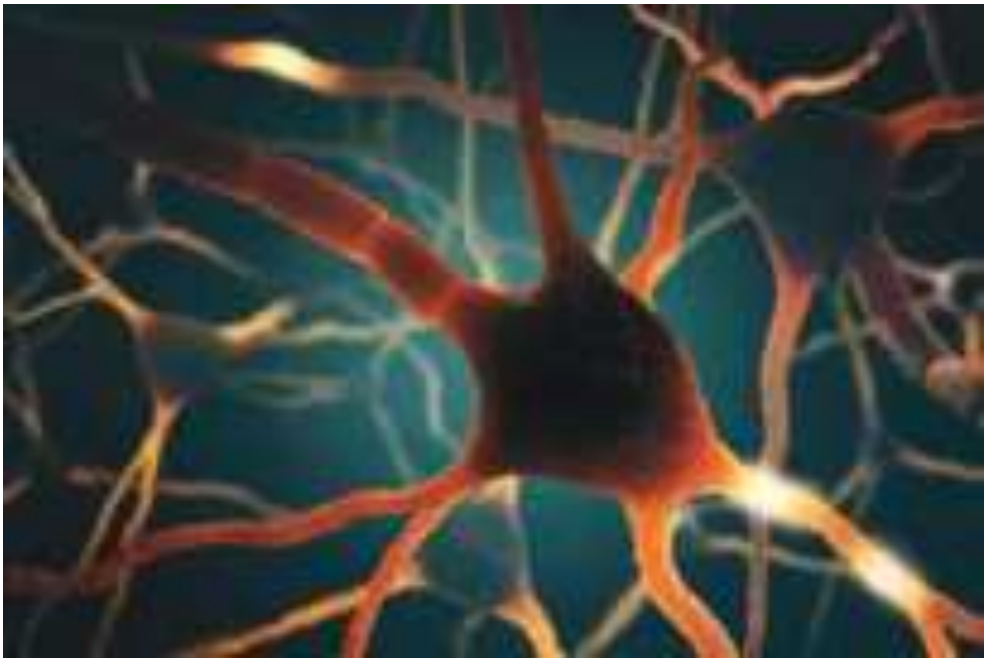
Chapter 4

Neural Conduction and Synaptic Transmission

How Neurons Send and Receive Signals



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Chapter Overview and Learning Objectives

Resting Membrane Potential	**LO 4.1**	Describe how the membrane potential is recorded.
	LO 4.2	Describe the resting membrane potential and its ionic basis, and describe the three factors that influence the distribution of Na^+ and K^+ ions across the neural membrane.
Generation, Conduction, and Integration of Postsynaptic Potentials	**LO 4.3**	Describe the types of postsynaptic potentials and how they are conducted.
	LO 4.4	Describe how postsynaptic potentials summate and how action potentials are generated.
Conduction of Action Potentials	**LO 4.5**	Explain the ionic basis of an action potential.
	LO 4.6	Explain how the refractory period is responsible for two important characteristics of neural activity.

	LO 4.7 Describe how action potentials are conducted along axons—both myelinated and unmyelinated.
	LO 4.8 Explain the shortcomings of the Hodgkin-Huxley model when applied to neurons in the mammalian brain.
Synaptic Transmission: From Electrical Signals to Chemical Signals	**LO 4.9** Describe the structure of different types of synapses.
	LO 4.10 Describe how neurotransmitter molecules are synthesized and packaged in vesicles.
	LO 4.11 Explain the process of neurotransmitter exocytosis.
	LO 4.12 Describe the differences between ionotropic and metabotropic receptors.
	LO 4.13 Explain how neurotransmitters are removed from a synapse.
	LO 4.14 Describe the roles of glia and gap junctions in synaptic transmission.
Neurotransmitters	**LO 4.15** Name the major classes of neurotransmitters.
	LO 4.16 Identify the class, and discuss at least one function of each of the neurotransmitters discussed in this section.
Pharmacology of Synaptic Transmission and Behavior	**LO 4.17** Provide a general overview of how drugs influence synaptic transmission.
	LO 4.18 Describe three examples of how drugs have been used to influence neurotransmission.

The Lizard: A Case of Parkinson's Disease*

"I have become a lizard," he began. "A great lizard frozen in a dark, cold, strange world."

His name was Roberto Garcia d'Orta. He was a tall thin man in his sixties, but like most patients with Parkinson's disease, he appeared to be much older than his actual age. Not many years before, he had been an active, vigorous businessman. Then it happened—not all at once, not suddenly, but slowly, subtly, insidiously. Now he turned like a piece of granite, walked in slow shuffling steps, and spoke in a monotonous whisper.

What had been his first symptom?

A tremor.

Had his tremor been disabling?

"No," he said. "My hands shake worse when they are doing nothing at all"—a symptom called *tremor-at-rest*.

The other symptoms of Parkinson's disease are not quite so benign. They can change a vigorous man into a lizard. These include rigid muscles, a marked poverty of spontaneous movements, difficulty in starting to move, and slowness in executing voluntary movements once they have been initiated.

The term *reptilian stare* is often used to describe the characteristic lack of blinking and the widely opened eyes gazing out of a motionless face, a set of features that seems more reptilian than human. Truly a lizard in the eyes of the world.

What was happening in Mr. d'Orta's brain? A group of neurons called the *substantia nigra* (black substance) were unaccountably dying. These neurons make a particular chemical called dopamine, which they deliver to another part of the brain, known as the *striatum*. As the cells of the substantia nigra die, the amount of dopamine they can deliver to the cells in the striatum goes down. The striatum helps control movement, and to do that normally, it needs dopamine.

*Based on *Newton's Madness* by Harold Klawans (Harper & Row, 1990). Reprinted by permission of Jet Literary Associates, Inc.

Although dopamine levels are low in Parkinson's disease, dopamine is not an effective treatment because it does not readily penetrate the blood–brain barrier. However, knowledge of dopaminergic transmission has led to the development of an effective treatment: *L-dopa*, the chemical precursor of dopamine, which readily penetrates the blood–brain barrier and is converted to dopamine once inside the brain.

Mr. d'Orta's neurologist prescribed *L-dopa*, and it worked. He still had a bit of tremor, but his voice became stronger, his feet no longer shuffled, his reptilian stare faded away, and he was once again able to perform with ease many of the activities of daily life (e.g., eating, bathing, writing, speaking, and even having sex with his wife). Mr. d'Orta had been destined to spend the rest of his life trapped inside a body that was becoming increasingly difficult to control, but his life sentence was repealed—at least temporarily.

Mr. d'Orta's story does not end here. For the purposes of this chapter, his case illustrates why knowledge of the fundamentals of neural conduction and synaptic transmission is a must for any biopsychologist (see Südhof, 2017).

This chapter is about neural communication: How signals are sent from cell to cell, within networks of cells. This is not unlike what happens in a social network: Twitter is an illustrative example.

When a person in a social network tweets a message, that message is carried to other people. If the message isn't compelling enough, it gets lost in the void. If it is compelling, then some will retweet the message, propagating it to more people in their own social networks, and so on. Likewise, when a cell in our brain sends a message to the cells in its network, if the message is strong enough, some of those cells will propagate the message to other cells in their networks, and so on. Conversely, if the message isn't strong enough, the message will be lost.

Resting Membrane Potential

In order to understand how a message is conducted within neurons or transmitted from one neuron to another, you have to first learn about the **membrane potential**: the difference in electrical charge between the inside and the outside of a cell.

Recording the Membrane Potential

LO 4.1 Describe how the membrane potential is recorded.

To record a neuron's membrane potential, it is necessary to position the tip of one electrode inside the neuron and the tip of another electrode outside the neuron in the extracellular fluid. Although the size of the extracellular electrode is not critical, the tip of the intracellular electrode must be fine enough to pierce the neural membrane without damaging it. The intracellular electrodes are called **microelectrodes**; their tips are less than one-thousandth of a millimeter in diameter—much too small to be seen by the naked eye.

When both electrode tips are in the extracellular fluid, the voltage difference between them is zero. However, when the tip of the intracellular electrode is inserted into a neuron that is *at rest* (not receiving signals from other cells), a steady potential of about –70 millivolts (mV) is recorded. This indicates that the potential inside the resting neuron is about 70 mV less than that outside the neuron. This steady membrane potential of about –70 mV is called the neuron's **resting potential**. In its resting state, with the –70 mV charge built up across its membrane, a neuron is said to be **polarized** (it has a membrane potential that is not zero).

Ionic Basis of the Resting Potential

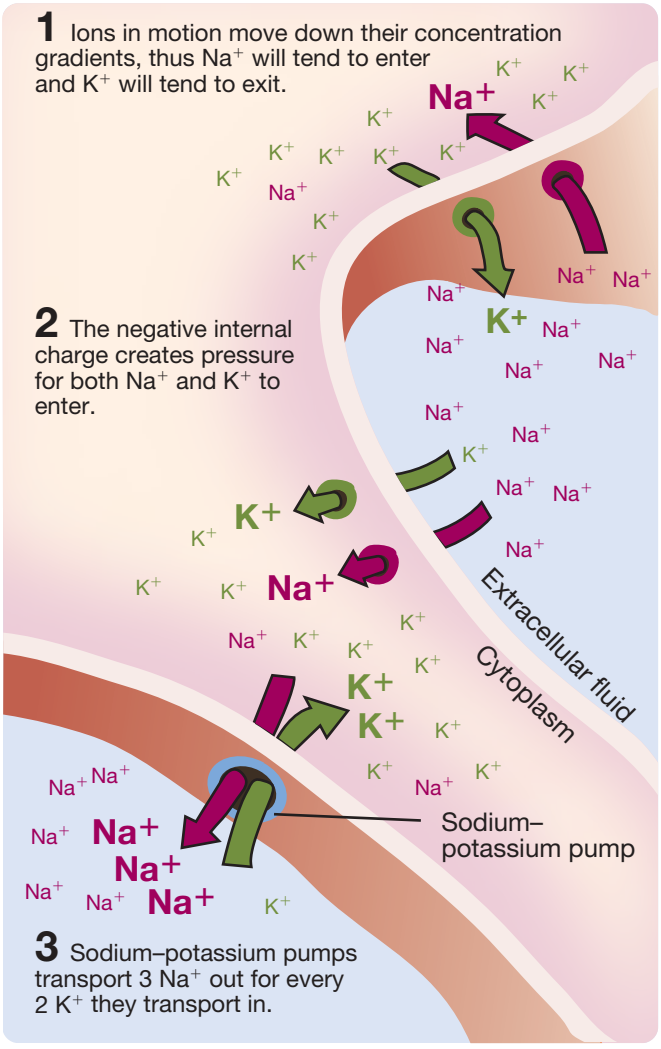
LO 4.2 Describe the resting membrane potential and its ionic basis, and describe the three factors that influence the distribution of Na^+ and K^+ ions across the neural membrane.

Like all salts in solution, the salts in neural tissue separate into positively and negatively charged particles called **ions**. There are many different kinds of ions in neurons, but this discussion focuses on only two of them: sodium ions and potassium ions. The abbreviations for sodium ions (Na^+) and potassium ions (K^+) are derived from their Latin names: *natrium* (Na) and *kalium* (K). The plus signs indicate that each Na^+ and K^+ ion carries a single positive charge.

In resting neurons, there are more Na^+ ions outside the cell than inside and more K^+ ions inside than outside. These unequal distributions of Na^+ and K^+ ions are maintained even though there are specialized pores in the neural membrane, called **ion channels**. Each type of ion channel is specialized for the passage of particular ions (e.g., Na^+ or K^+). For example, some ion channels are specialized for the passage of Na^+ ions, K^+ ions, or other ions.

There is substantial pressure on Na^+ ions to enter the resting neurons. This pressure is of two types. First is the *electrostatic pressure* from the resting membrane potential: Because opposite charges attract, the positively charged Na^+ ions are attracted to the –70 mV charge inside resting neurons. Second is the pressure from *random motion* for Na^+ ions to move down their *concentration gradient*. Let us explain. Like all ions in solution, the ions in neural tissue

Figure 4.1 Three factors that influence the distribution of Na^+ and K^+ ions across neural membranes, illustrated in a resting neuron.



are in constant random motion, and particles in random motion tend to become evenly distributed because they are more likely to move down their *concentration gradients* than up them; that is, they are more likely to move from areas of high concentration to areas of low concentration than vice versa. Likewise, a drop of red ink placed in a bathtub full of water will move outwards to areas where there is no ink, and the water will gradually turn pink.

So, why then do Na^+ ions under electrostatic pressure and pressure from random movement not come rushing into neurons, thus reducing the resting membrane potential? The answer is simple: The sodium ion channels in resting neurons are closed, thus greatly reducing the flow of Na^+ ions into the neuron. In contrast, the potassium ion channels are open in resting neurons, but only a few K^+ ions exit because the electrostatic pressure that results from the negative resting membrane potential largely holds them inside.

In the 1950s, Alan Hodgkin and Andrew Huxley became interested in the stability of the resting membrane potential. Some Na^+ ions do manage to enter resting neurons despite the closed sodium channels and some K^+ ions do exit; then why does the resting membrane potential stay fixed? In a series of clever experiments, for which they were awarded Nobel Prizes, Hodgkin and Huxley discovered the answer. At the same rate that Na^+ ions leaked into resting neurons, other Na^+ ions were actively transported out; and at the same rate that K^+ ions leaked out of resting neurons, other K^+ ions were actively transported in. Such ion transport is performed by mechanisms in the cell membrane that continually exchange three Na^+ ions inside the neuron for two K^+ ions outside. These transporters are commonly referred to as **sodium–potassium pumps**.

Since the discovery of sodium–potassium pumps, several other classes of **transporters** (mechanisms in the membrane of a cell that actively transport ions or molecules across the membrane) have been discovered (see Kaila et al., 2014). You will encounter more of them later in this chapter.

Figure 4.1 summarizes the status of Na^+ and K^+ ions in a resting neuron. Now that you understand the basic properties of resting neurons, you are prepared to consider how neurons respond to input signals.

Generation, Conduction, and Integration of Postsynaptic Potentials

What happens when a resting membrane potential is disturbed? Typically, disturbances of the membrane potential occur as a result of input from cells that synapse on a neuron. For that reason, such disturbances of the resting membrane potential are termed **postsynaptic potentials (PSPs)**. In this module, you will learn how PSPs are generated by input to a neuron, how they are subsequently conducted to different parts of a neuron, and how they can cause a neuron to fire (produce an action potential).

Generation and Conduction of Postsynaptic Potentials

LO 4.3 **Describe the types of postsynaptic potentials and how they are conducted.**

When neurons fire, they release from their terminal buttons chemicals called *neurotransmitters*, which diffuse across the synaptic clefts and interact with specialized receptor molecules on the receptive membranes of the next neuron in the circuit. When neurotransmitter molecules bind

to postsynaptic receptors, they typically have one of two effects, depending on the neurotransmitter, receptor, and postsynaptic neuron in question. They may **depolarize** the receptive membrane (decrease the resting membrane potential, from –70 to –67 mV, for example), or they may **hyperpolarize** it (increase the resting membrane potential, from –70 to –72 mV, for example).

Postsynaptic depolarizations are called **excitatory postsynaptic potentials (EPSPs)** because, as you will soon learn, they increase the likelihood that the neuron will fire. Postsynaptic hyperpolarizations are called **inhibitory postsynaptic potentials (IPSPs)** because they decrease the likelihood that the neuron will fire.

All PSPs, both EPSPs and IPSPs, are **graded potentials**. This means that the amplitudes of PSPs are proportional to the intensity of the signals that elicit them: Weak signals elicit small PSPs, and strong signals elicit large ones.

EPSPs and IPSPs travel passively from their sites of generation at synapses, usually on the dendrites or cell body, in much the same way that electrical signals travel through a cable. Accordingly, the transmission of PSPs has two important characteristics. First, it is *rapid*—so rapid that it can be assumed to be instantaneous for most purposes. It is important not to confuse the duration of PSPs with their rate of transmission; although the duration of PSPs varies considerably, all PSPs, whether brief or enduring, are transmitted almost instantaneously. Second, the transmission of PSPs is *decremental*: They decrease in amplitude as they travel through the neuron, just as a ripple on a pond gradually disappears as it travels outward. Most PSPs do not travel more than a couple of millimeters from their site of generation before they fade out completely.

Integration of Postsynaptic Potentials and Generation of Action Potentials

LO 4.4 **Describe how postsynaptic potentials summate and how action potentials are generated.**

The PSPs created at a single synapse typically have little effect on the firing of the postsynaptic neuron. The receptive areas of most neurons are covered with thousands of synapses, and whether a neuron fires is determined by the net effect of their activity. More specifically, whether a neuron fires depends on the balance between the excitatory and inhibitory signals reaching its axon. It was once believed that action potentials were generated at the **axon hillock** (the conical structure at the junction between the cell body and the axon), but they are actually generated in the adjacent section of the axon, called the **axon initial segment** (see Kuba, Adachi, & Ohmori, 2014; Tian et al., 2014).

The graded EPSPs and IPSPs created by the action of neurotransmitters at particular receptive sites on a neuron's membrane are conducted instantly and decrementally to the axon initial segment. If the sum of the depolarizations and hyperpolarizations reaching the axon initial segment at any time is sufficient to depolarize the membrane to a level referred to as its **threshold of excitation**—usually about –65 mV—an action potential is generated. The **action potential (AP)** is a massive but momentary—lasting for 1 millisecond—reversal of the membrane potential from about –70 to about +50 mV. Unlike PSPs, APs are not graded responses: Their magnitude is not related in any way to the intensity of the stimuli that elicit them. To the contrary, they are **all-or-none responses**; that is, they either occur to their full extent or do not occur at all. See Figure 4.2 for an

Figure 4.2 An EPSP, an IPSP, and an EPSP followed by an AP.

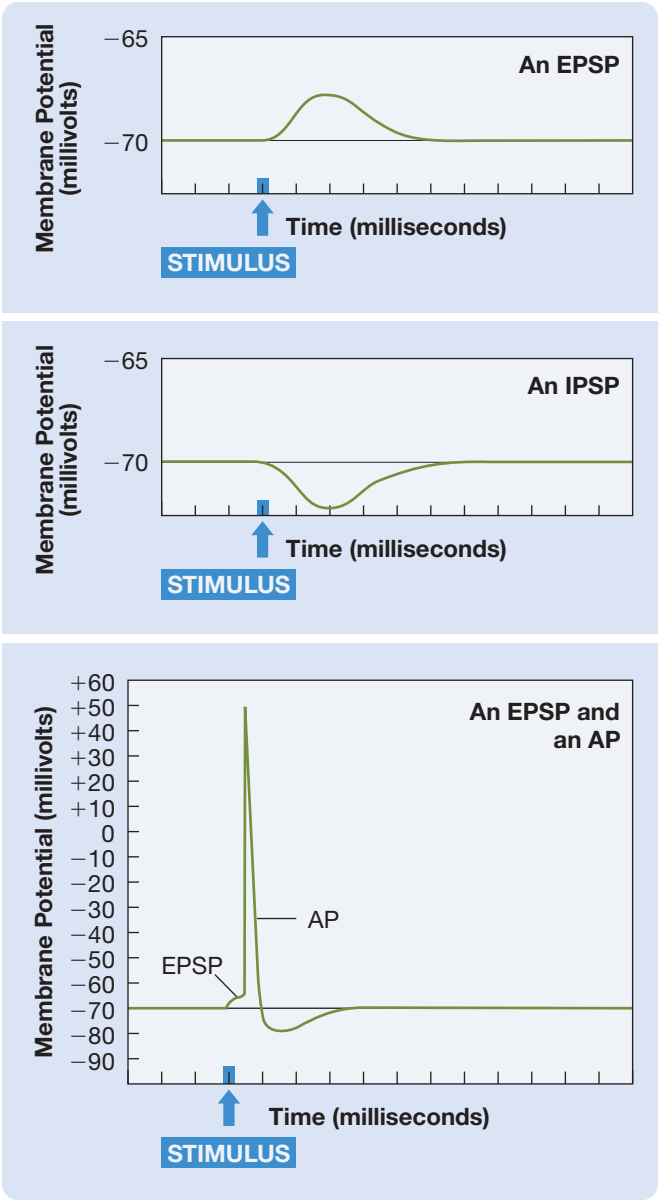


illustration of an EPSP, an IPSP, and an AP. Although many neurons display APs of the type illustrated in Figure 4.2, others do not—for example, some neurons display APs that have a longer duration, have a lower amplitude, or involve multiple spikes.

In effect, each neuron adds together all the graded excitatory and inhibitory PSPs reaching its axon initial segment and decides to fire or not to fire on the basis of their sum. The summation of PSPs occurs in two ways: over space and over time.

Figure 4.3 shows the three possible combinations of **spatial summation**. It shows how local EPSPs that are produced simultaneously on different parts of the receptive membrane sum to form a greater EPSP, how simultaneous IPSPs sum to form a greater IPSP, and how simultaneous EPSPs and IPSPs sum to cancel each other out.

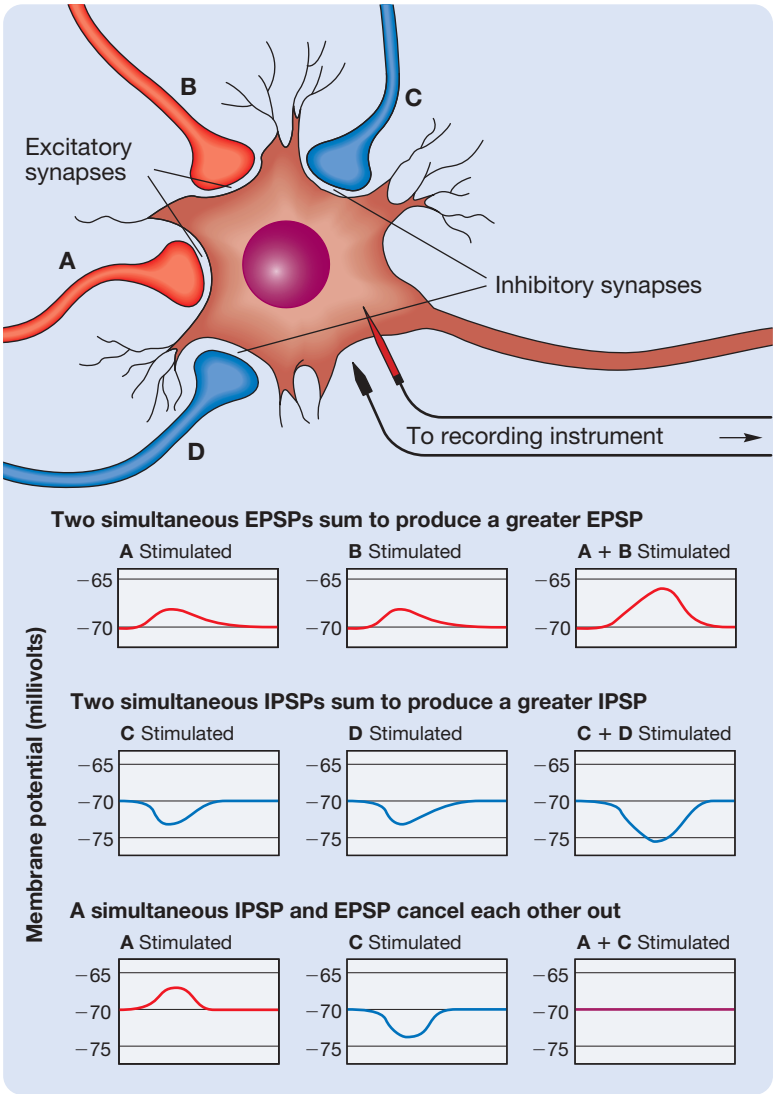
Figure 4.4 illustrates **temporal summation**. It shows how PSPs produced in rapid succession at the same synapse sum to form a greater signal. The reason that successive stimulations of a neuron can add together over time is that the PSPs they produce often outlast them. Thus, if a particular synapse is activated and then activated again before the original PSP has completely dissipated, the effect of the second stimulation will be superimposed on the lingering PSP produced by the first. Accordingly, it is possible for a brief subthreshold excitatory stimulus to fire a neuron if it is administered twice in rapid succession. In the same way, an inhibitory synapse activated twice in rapid succession can produce a greater IPSP than that produced by a single stimulation.

PSPs continuously summate over both time and space as a neuron is continually bombarded with stimuli from thousands of synapses. Although schematic diagrams of neural circuitry rarely show neurons with more than a few representative synaptic contacts, most neurons have thousands of synaptic contacts covering their dendrites and cell body. To better understand the summation of PSPs, consider what happens to the many ripples on the surface of a pond: The ripples are continuously interacting with each other to generate larger or smaller ripples.

The location of a synapse on a neuron's membrane had long been assumed to be an important factor in determining its potential to influence the neuron's firing. Because PSPs are transmitted decrementally, synapses near the axon had been assumed to have the most influence on the firing of the neuron. However, it has been demonstrated that some neurons have a mechanism for amplifying dendritic signals that originate far from their axon (see Adrian et al., 2014; Araya, 2014).

In some ways, the firing of a neuron is like the firing of a gun. Both reactions are triggered by graded responses. As a trigger is squeezed, it gradually moves back until it causes the gun to fire; as a neuron is stimulated, it becomes less polarized until the threshold of excitation is reached and firing occurs. Furthermore, the firing of a gun and neural firing are both all-or-none events. Just as squeezing a trigger harder does not make the bullet travel faster or farther, stimulating a neuron more intensely does not increase the speed or amplitude of the resulting action potential.

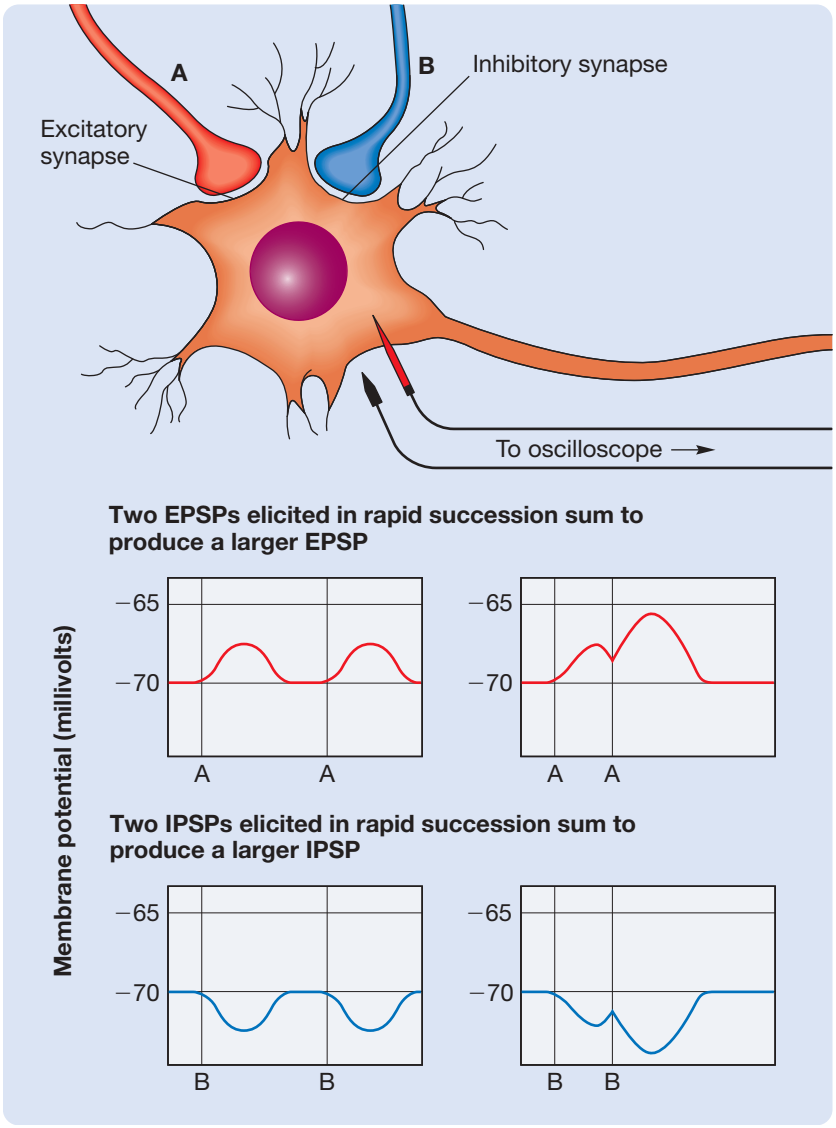
Figure 4.3 The three possible combinations of spatial summation.



Journal Prompt 4.1

Can you think of a metaphor, other than the firing of a gun, that might serve as an accurate description of the firing of a neuron?

Figure 4.4 The two possible combinations of temporal summation.



Scan Your Brain

This is a good place to pause and scan your brain to check your knowledge on synaptic transmission. Fill in the following blanks with the most appropriate terms. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. _____ is a common chemical used to alleviate symptoms in people living with Parkinson's disease.
2. The difference in electrical charge between the inside and outside of a nerve cell is called _____ and is recorded using microelectrodes.
3. The resting potential inside the neuron is approximately _____ mV less than that outside the cell. This is called polarization.
4. Sodium and potassium ions are both _____ charged.
5. In a resting neuron, there are more _____ ions outside the cell and more _____ ions inside the cell.
6. K^+ ions are largely held inside the cell because of the membrane's _____ resting potential.
7. _____ pumps ensure that at resting potential, three Na^+ ions move inside the cell and two K^+ ions move outside the cell.
8. _____ are released into the synaptic cleft, and they attach to receptor molecules on the postsynaptic membrane of the next cell.
9. The neurotransmitters may _____ the postsynaptic receptive membrane, which implies that the resting membrane potential will increase.
10. _____ postsynaptic potentials increase the likelihood that a neuron will fire.
11. Postsynaptic potentials _____ in amplitude as they travel through the neuron.

12. A momentary increase of membrane potential to about +50 mV is called _____.
13. Each neuron sums the number of excitatory and inhibitory postsynaptic potentials to create a single signal, a process called _____.
14. When postsynaptic potentials that are produced in rapid succession at the same synapse are added, we have _____ summation.
15. When postsynaptic potentials that are produced simultaneously in different parts of the receptive membrane are added, we have _____ summation.
16. The firing of neurons and the firing of a gun are both _____ responses.

Scan Your Brain answers: (1) L-*dopa*, (2) membrane potential, (3) 70, (4) positively, (5) Na^+, K^+, (6) negative, (7) Sodium–potassium, (8) Neurotransmitters, (9) hyperpolarize, (10) Excitatory, (11) decrease, (12) action potential, (13) integration, (14) temporal, (15) spatial, (16) all-or-none.

Conduction of Action Potentials

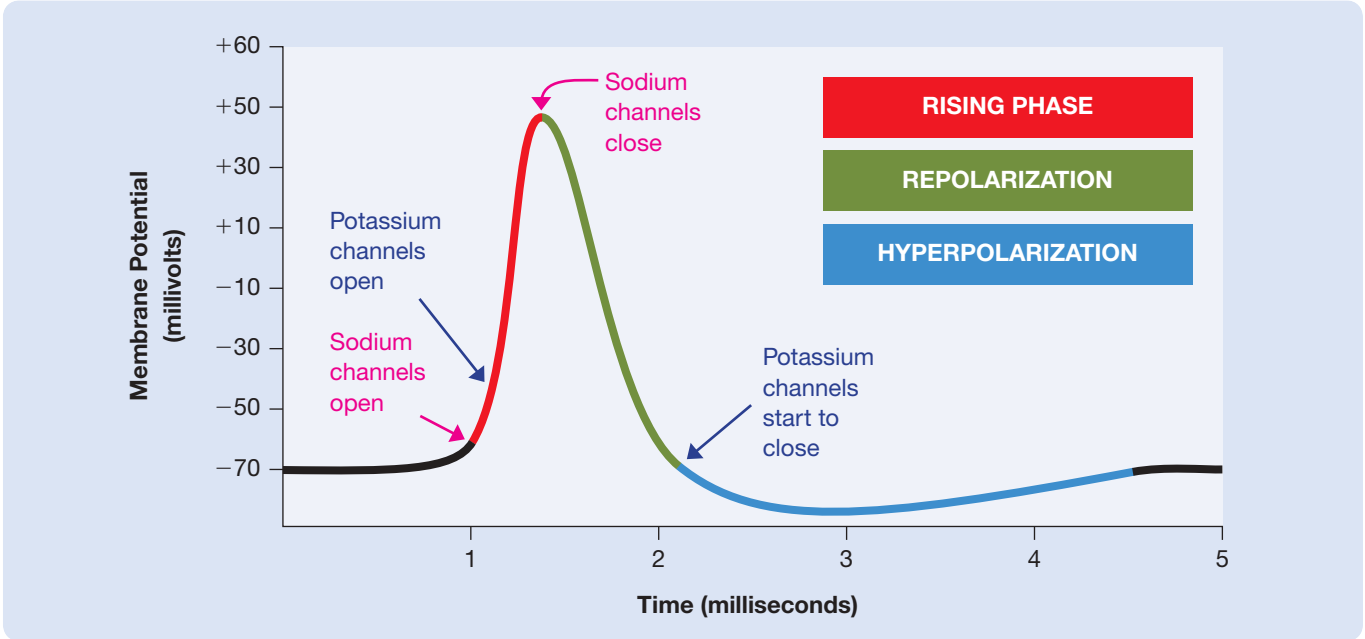
How are action potentials (APs) produced? How are they conducted along the axon? The answer to both questions is the same: through the action of **voltage-gated ion channels**—ion channels that open or close in response to changes in membrane potential (see Moran et al., 2015).

Ionic Basis of Action Potentials

LO 4.5 Explain the ionic basis of an action potential.

Recall that the membrane potential of a neuron at rest is relatively constant despite the high pressure acting to drive Na^+ ions into the cell. This is because the resting membrane is relatively impermeable to Na^+ ions and because those few that do pass in are pumped out. But things suddenly change when the membrane potential of the axon initial segment is depolarized to the threshold of excitation by a sufficiently large EPSP. The voltage-gated sodium channels in the axon membrane open wide, and Na^+ ions rush in, suddenly reversing the membrane potential; that is, driving the membrane potential from about −70 to about +50 mV. The rapid change in the membrane potential associated with the *influx* of Na^+ ions then triggers the opening of voltage-gated potassium channels. At this point, K^+ ions near the membrane are driven out of the cell through these channels—first by their relatively high internal concentration and then, when the AP is near its peak, by the positive internal charge. After about 1 millisecond, the sodium channels close. This closure marks the end of the *rising phase* of the AP and the beginning of the *repolarization phase*, which is the result of the continued efflux of K^+ ions. Once repolarization has been achieved, the potassium channels gradually close, which marks the beginning of the *hyperpolarization phase*. Because they close gradually, too many K^+ ions flow out of the neuron, and it is left hyperpolarized for a brief period of time. Figure 4.5 illustrates the timing of the opening and closing of the sodium and potassium channels during an AP, and the three associated phases of an AP.

Figure 4.5 The opening and closing of voltage-gated sodium and potassium channels during an AP, and the three associated phases of an AP.



The number of ions that flow through the membrane during an AP is extremely small in relation to the total number inside and around the neuron. The AP involves only those ions right next to the membrane. Therefore, a single AP has little effect on the relative concentrations of various ions inside and outside the neuron, and the resting ion concentrations next to the membrane are rapidly reestablished by the random movement of ions. The sodium–potassium pumps play only a minor role in the reestablishment of the resting potential.

Refractory Periods

LO 4.6 Explain how the refractory period is responsible for two important characteristics of neural activity.

There is a brief period of about 1 to 2 milliseconds after the initiation of an AP during which it is impossible to elicit a second AP. This period is called the **absolute refractory period**. The absolute refractory period is followed by the **relative refractory period**—the period during which it is possible to fire the neuron again but only by applying higher-than-normal levels of stimulation. The end of the relative refractory period is the point at which the amount of stimulation necessary to fire the neuron returns to baseline.

Refractory periods are responsible for two important characteristics of neural activity. First, they are responsible for the fact that APs normally travel along axons in only one direction. Because the portions of an axon over which an AP has just traveled are left momentarily refractory, an AP cannot reverse direction. Second, refractory periods are responsible for the fact that the rate of neural firing is related to the intensity of the stimulation. If a neuron is subjected to continual high-intensity stimulation, it fires and then fires again as soon as its absolute refractory period is over—a maximum of about 1,000 times per second. However, if the level of continuous stimulation is of an intensity just sufficient to fire the neuron when it is at rest, the neuron does not fire again until both the absolute and the relative refractory periods have run their course. Intermediate intensities of continuous stimulation produce intermediate rates of neural firing.

Axonal Conduction of Action Potentials

LO 4.7 Describe how action potentials are conducted along axons—both myelinated and unmyelinated.

The conduction of APs along an axon differs from the conduction of PSPs in two important ways. First, the conduction of APs along an axon is typically *nondecremental*; APs do not grow weaker as they travel along the axonal membrane. Second, APs are conducted more slowly than PSPs.

These two differences are the result of the important role played by voltage-gated sodium channels in AP conduction. Once an AP has been generated, it travels along the axon as a graded potential; that is, it travels rapidly and decrementally. However, when that graded potential reaches the next voltage-gated sodium channel along the axon, and if it is sufficiently large (i.e., it exceeds the threshold of excitation), then those channels open and Na^+ ions rush into the axon and generate another full-blown AP. In essence, the AP is continually regenerated at each sodium channel along the length of the axon, again and again until a full-blown AP is triggered as the axon terminal buttons.

The following analogy may help you appreciate the major characteristics of axonal conduction. Consider a row of mouse traps on a wobbly shelf, all of them set and ready to be triggered. Each trap stores energy by holding back its striker against the pressure of the spring, in the same way that each voltage-gated sodium channel stores energy by holding back Na^+ ions, which are under pressure to move down their concentration and electrostatic gradients into the neuron. When the first trap in the row is triggered, the vibration is transmitted through the shelf rapidly and decrementally. When the vibration reaches the next trap and it is sufficiently large, then that trap is sprung—and so on down the line. Likewise, when a sodium channel at the axon initial segment is opened by an EPSP, an AP is generated and then that electrical signal travels instantly and decrementally (i.e., as a graded potential) to the next sodium channel along the axon. Then, that sodium channel opens to generate an AP, and so on down the length of the axon.

Journal Prompt 4.2

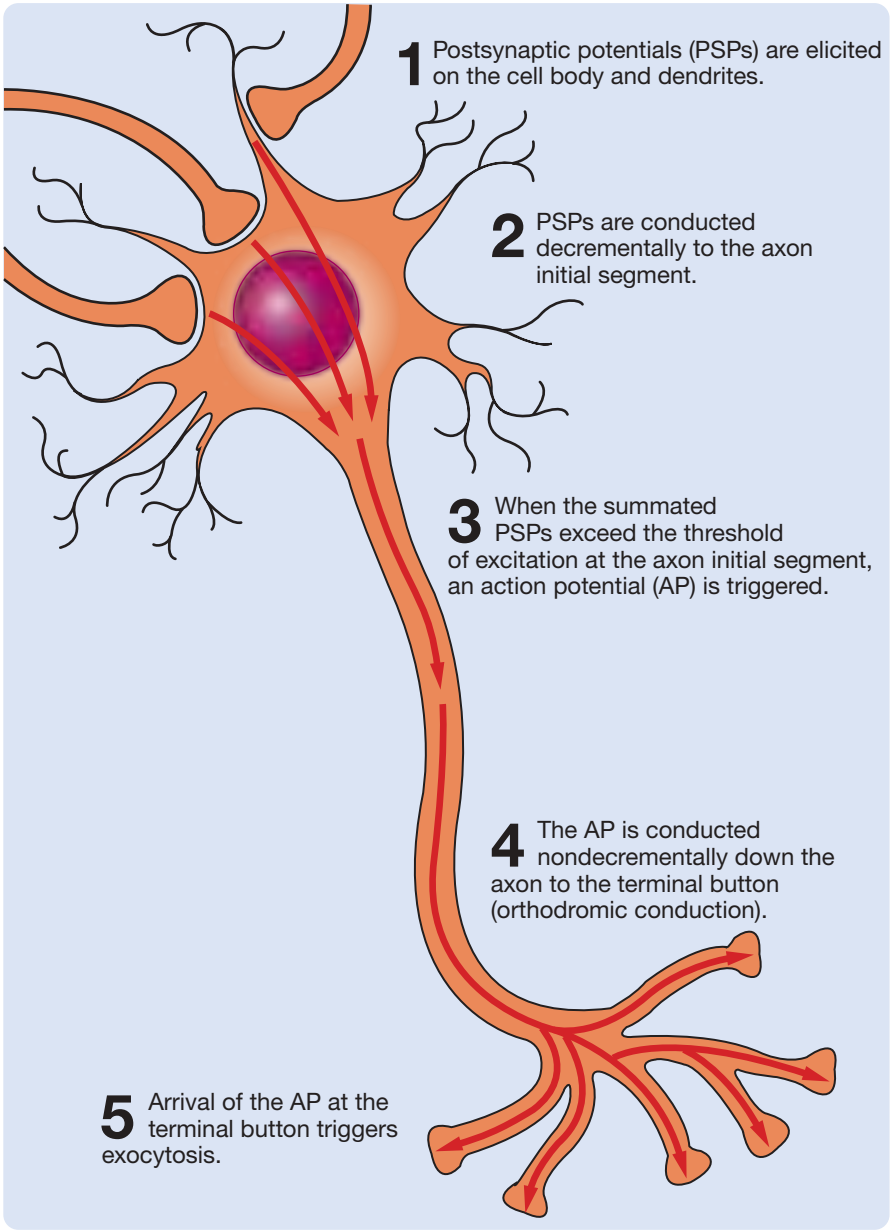
Can you think of a better analogy to describe axonal conduction?

The nondecremental nature of AP conduction is readily apparent from this analogy; the last trap on the shelf strikes with no less intensity than did the first. This analogy also illustrates another important point: The row of traps can transmit in either direction, just like an axon. If electrical stimulation of sufficient intensity is applied to a midpoint of an axon, two APs will be generated: One AP will travel along the axon back to the cell body—this is called **antidromic conduction**; the second AP will travel along the axon towards the terminal buttons—this is called **orthodromic conduction**. The elicitation of an AP and its orthodromic conduction are illustrated in Figure 4.6.

The generation of an AP at the axon initial segment also spreads back through the cell body and dendrites of the neuron as a large graded potential. It is believed that these antidromic (*backpropagating*) potentials play a role in certain forms of synaptic plasticity (see Stuart & Spruston, 2015).

CONDUCTION IN MYELINATED AXONS. Recall that the axons of many neurons are insulated from the extracellular fluid by segments of fatty tissue called *myelin*. In myelinated axons, ions can pass through the axonal membrane only at the **nodes of Ranvier**—the gaps between adjacent myelin segments.

Figure 4.6 The usual direction of signals conducted through a multipolar neuron (i.e., orthodromic conduction).



Indeed, in myelinated axons, axonal voltage-gated sodium channels are concentrated at the nodes of Ranvier. How, then, are APs transmitted in myelinated axons?

If we consider the mouse trap metaphor again, the answer is quite simple: It is just as if the mouse traps were placed further apart along the wobbly shelf. That is, because the sodium channels are concentrated at some distance from one another (at the nodes of Ranvier), the electrical signal generated at the sodium channels at one node of Ranvier travels instantly and decrementally (i.e., it is a graded potential) to the sodium channels at the next node, and so on down the length of the myelinated axon.

Myelination increases the speed of axonal conduction. Because conduction along the myelinated segments of the axon is instantaneous (i.e., it is a graded potential), the signal "jumps" along the axon from one node of Ranvier to the next. There is, of course, a slight delay at each node while the AP is regenerated, but conduction is still much faster in myelinated axons than in unmyelinated axons. The transmission of APs in myelinated axons is called **saltatory conduction** (*saltare* means "to skip or jump"). Given the important role of myelin in neural conduction, it is hardly surprising that diseases that damage the nervous system by attacking myelin, like multiple sclerosis, have devastating effects on neural activity and behavior.

THE VELOCITY OF AXONAL CONDUCTION. At what speed are APs conducted along an axon? The answer to this question depends on two properties of the axon. Conduction is faster in large-diameter axons, and—as you have just learned—it is faster in those that are myelinated. Human *motor neurons* (neurons that synapse on skeletal muscles) are large and myelinated; thus, some can conduct at speeds up to 60 meters per second (about 134 miles per hour). In contrast, small, unmyelinated axons conduct APs at about 1 meter per second.

CONDUCTION IN NEURONS WITHOUT AXONS. APs are the means by which axons conduct all-or-none signals nondecrementally over relatively long distances. Thus, to keep what you have just learned about APs in perspective, it is important for you to remember that most neurons in mammalian brains either do not have axons or have very short ones, and many of these neurons do not normally display APs. Conduction in these *interneurons* is typically only through graded potentials.

The Hodgkin-Huxley Model in Perspective

LO 4.8 Explain the shortcomings of the Hodgkin-Huxley model when applied to neurons in the mammalian brain.

The preceding account of neural conduction is based largely on the *Hodgkin-Huxley model*, the theory first proposed by Hodgkin and Huxley in the early 1950s (see Catterall et al., 2012). Perhaps you have previously encountered some of

this information about neural conduction in introductory biology or psychology courses, where it is often presented as a factual account of neural conduction and its mechanisms, rather than as a theory. To be fair, the Hodgkin-Huxley model was a major advance in our understanding of neural conduction (Catterall et al., 2012). Fully deserving of the 1963 Nobel Prize, the model provided a simple, effective introduction to what we now understand about the general ways in which neurons conduct signals. The problem is that the simple neurons and mechanisms of the Hodgkin-Huxley model are not representative of the variety, complexity, and plasticity of many of the neurons in the mammalian brain.

The Hodgkin-Huxley model was based on the study of squid motor neurons. Motor neurons are simple, large, and readily accessible in the PNS—squid motor neurons are particularly large. The simplicity, size, and accessibility of squid motor neurons contributed to the initial success of Hodgkin's and Huxley's research, but these same properties make it difficult to apply the model directly to the mammalian brain. Hundreds of different kinds of neurons are found in the mammalian brain, and many of these have actions not found in motor neurons.

Moreover, there is mounting evidence that neural conduction is not merely due to electrical impulses (see Holland, De Regt, & Drukarch, 2019). For example, there is evidence that electrical impulses, like APs or PSPs, are accompanied by mechanical impulses: travelling waves of expansion and contraction of the neural membrane—exactly like ripples on a pond (see Fox, 2018). In summary, the Hodgkin-Huxley model should be applied to cerebral neurons with great caution.

Synaptic Transmission: From Electrical Signals to Chemical Signals

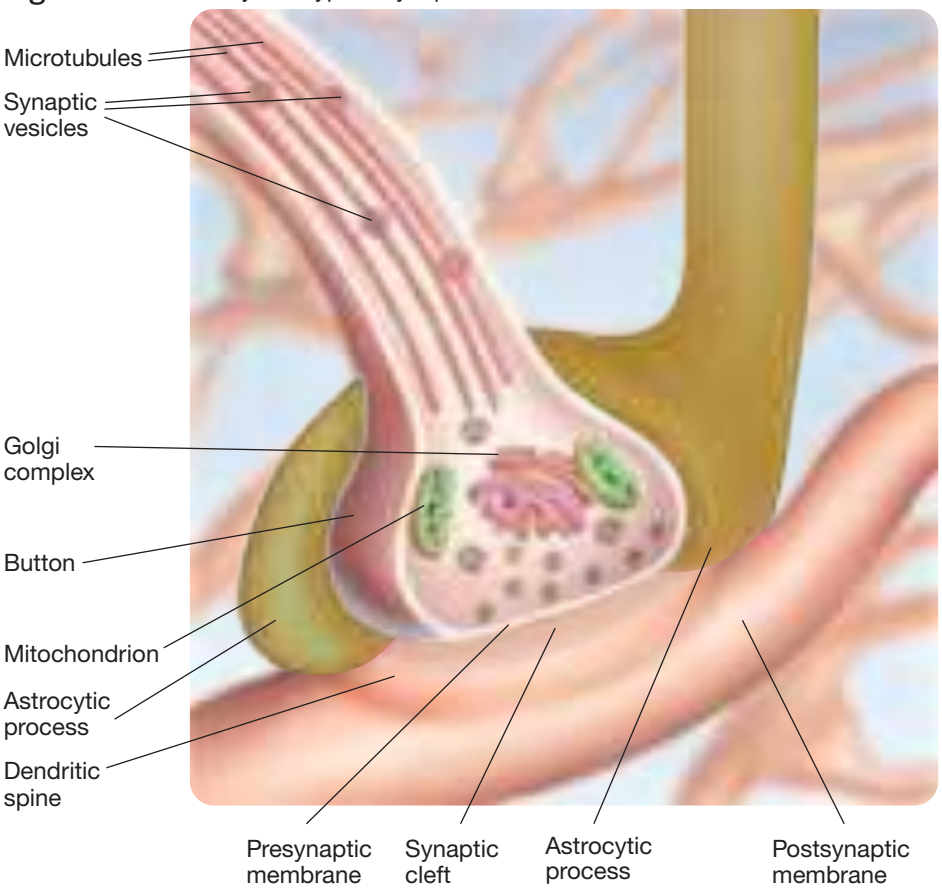
Now that you have learned about how communication occurs within a single neuron—through postsynaptic potentials (PSPs) and action potentials (APs)—you are ready to learn how neurons communicate with other cells. In the remaining modules of this chapter, you will learn how APs arriving at terminal buttons trigger the release of neurotransmitters into synapses and how neurotransmitters carry signals to other cells. This module provides an overview of five aspects of synaptic transmission: (1) the structure of synapses; (2) the synthesis, packaging, and transport of neurotransmitter molecules; (3) the release of neurotransmitter molecules; (4) the activation of receptors by neurotransmitter molecules; and (5) the reuptake, enzymatic degradation, and recycling of neurotransmitter molecules.

Structure of Synapses

LO 4.9 Describe the structure of different types of synapses.

Some communication among neurons occurs across synapses such as the one illustrated in Figure 4.7. At such synapses, neurotransmitter molecules are released from specialized sites on buttons into synaptic clefts, where they induce EPSPs or IPSPs in other neurons by binding to receptors on their postsynaptic membranes. The synapse featured in Figure 4.7 is an *axodendritic synapse*—a synapse of an axon terminal button onto a dendrite. Also common are *axosomatic synapses*—-synapses of axon terminal buttons on *somas* (cell bodies). Notice in Figure 4.7 that many axodendritic synapses terminate on **dendritic spines** (nodules of various shapes that are located on the surfaces of many dendrites)—see Figure 3.30. Also notice in Figure 4.7 that an astrocyte is situated at the synapse. Most synapses in the brain form a **tripartite synapse**: a synapse that involves two neurons and

Figure 4.7 Anatomy of a typical synapse.

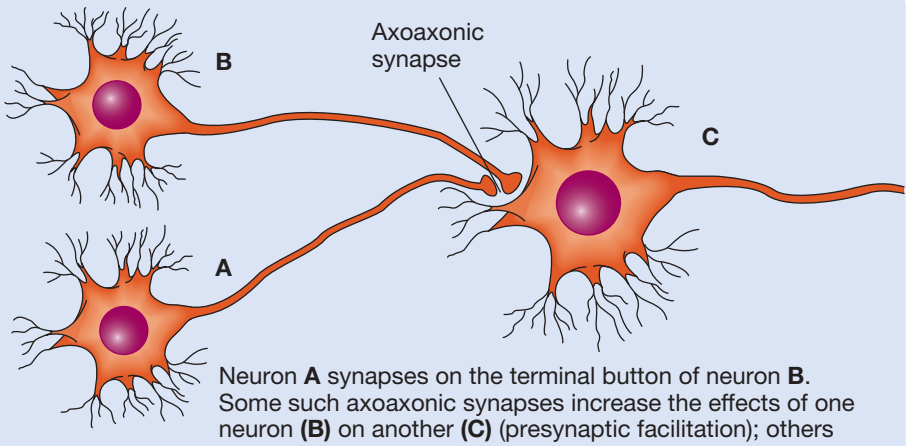


an astroglial cell (see Allen & Eroglu, 2017; Grosche & Reichenbach, 2013; Navarrete & Araque, 2014; Sun et al., 2013). All three cells communicate with one another through synaptic transmission.

Although axodendritic and axosomatic synapses are the most common synaptic arrangements, there are many others (see Matthews & Fuchs, 2010). For example, there are *dendrodendritic synapses*, which are interesting because they are often capable of transmission in either direction (see Urban & Castro, 2010). There are also *axoaxonic synapses*; these are particularly important because they can mediate *presynaptic facilitation and inhibition*. As illustrated in Figure 4.8, an axoaxonic synapse on or near a terminal button can selectively facilitate or inhibit the effects of that button on the postsynaptic neuron. The advantage of presynaptic facilitation and inhibition (compared to PSPs) is that they can selectively influence one particular synapse rather than the entire presynaptic neuron. Finally, in the central nervous system, there are also *axomyelenic synapses*, where an axon synapses on the myelin sheath of an oligodendrocyte. This newly discovered type of synapse represents yet another form of neuron–glia communication (see Dimou & Simons, 2017; Micu et al., 2018).

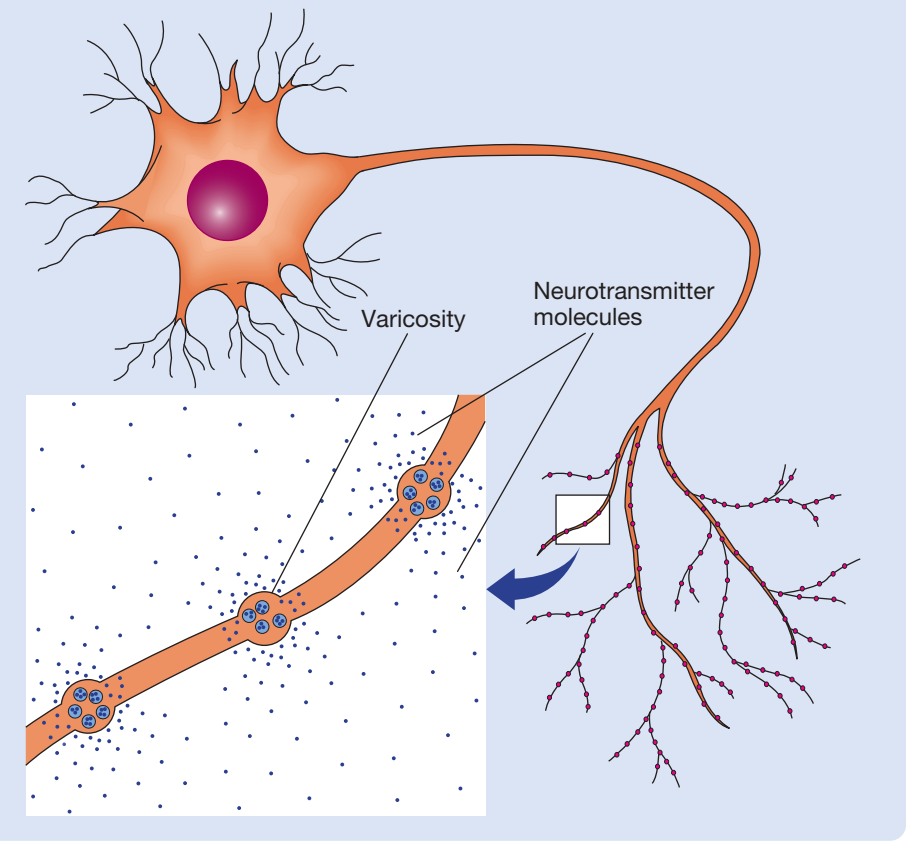
The synapses depicted in Figures 4.7 and 4.8 are **directed synapses**—synapses at which the site of neurotransmitter release and the site of neurotransmitter reception are in close proximity. This is a common arrangement, but there are also many nondirected synapses in the mammalian nervous system. **Nondirected synapses** are synapses at which the site of release is at some distance from the site of reception. One type of nondirected synapse is depicted in Figure 4.9. In this type of arrangement, neurotransmitter

Figure 4.8 Presynaptic facilitation and inhibition.



Neuron **A** synapses on the terminal button of neuron **B**. Some such axoaxonic synapses increase the effects of one neuron **(B)** on another **(C)** (presynaptic facilitation); others decrease the effects of one neuron **(B)** on another **(C)** (presynaptic inhibition). The advantage of presynaptic facilitation and inhibition is that they selectively influence single synapses, rather than the entire neuron.

Figure 4.9 One example of nondirected neurotransmitter release. Some neurons release neurotransmitter molecules diffusely from varicosities along the axon and its branches.



molecules are released from a series of *varicosities* (bulges or swellings) along the axon and its branches and thus are widely dispersed to surrounding targets. Because of their appearance, these synapses are often referred to as *string-of-beads synapses*.

Synthesis, Packaging, and Transport of Neurotransmitter Molecules

LO 4.10 Describe how neurotransmitter molecules are synthesized and packaged in vesicles.

There are two basic categories of neurotransmitter molecules: large and small.

All large neurotransmitters are neuropeptides. **Neuropeptides** are short amino acid chains composed of between 3 and 36 amino acids; in effect, they are short proteins.

Small-molecule neurotransmitters are typically synthesized in the cytoplasm of the terminal button and packaged in **synaptic vesicles** by the button's **Golgi complex**. (This may be a good point at which to review the internal structures of neurons in Figure 3.6.) Once filled with neurotransmitter, the vesicles are stored in clusters next to the presynaptic membrane. In contrast, neuropeptides, like other proteins, are assembled in the cytoplasm of the cell body on *ribosomes*; they are then packaged in vesicles by the cell body's Golgi complex and transported by *microtubules* to the terminal buttons at a rate of about 40 centimeters (about 16 inches) per day. The vesicles that contain neuropeptides are usually larger than those that contain small-molecule neurotransmitters, and they do not usually congregate as closely to the presynaptic membrane as the other vesicles do.

It was once believed that each neuron synthesizes and releases only one neurotransmitter, but it has been clear for some time that many neurons contain two neurotransmitters—a situation generally referred to as **coexistence**. It may have escaped your notice that the button illustrated in Figure 4.7 contains synaptic vesicles of two sizes. This suggests that it contains two neurotransmitters: a neuropeptide in the larger vesicles and a small-molecule neurotransmitter in the smaller vesicles. Although this type of coexistence was the first to be discovered, we now know that there is also coexistence of multiple small-molecule neurotransmitters in the same neuron (see Granger, Wallace, & Sabatini, 2017). Adding to the complexity is the fact that neurons can change the types of neurotransmitters they release over their lifespan (see Spitzer, 2017).

Release of Neurotransmitter Molecules

LO 4.11 Explain the process of neurotransmitter exocytosis.

Exocytosis—the process of neurotransmitter release—is illustrated in Figure 4.10 (see Shin, 2014). When a neuron is at rest, synaptic vesicles that contain small-molecule neurotransmitters tend to congregate near sections of the presynaptic membrane that are particularly rich in *voltage-gated calcium channels* (see Simms & Zamponi, 2014). When stimulated by APs, these channels open, and Ca^{2+} (*calcium*) ions enter the button. The entry of the Ca^{2+} ions triggers a chain reaction that ultimately causes synaptic vesicles to fuse with the presynaptic membrane and empty their contents into the synaptic cleft (see Zhou et al., 2017).

The release of small-molecule neurotransmitters differs from the release of neuropeptides. Small-molecule neurotransmitters are typically released in a pulse each time an AP triggers a momentary influx of Ca^{2+} ions into the presynaptic membrane; in contrast, neuropeptides are typically released gradually in response to general increases in the level of intracellular Ca^{2+} ions, such as might occur during a general increase in the rate of neuron firing.

It is important to note that not all vesicles fuse with the presynaptic membrane. Some vesicles are released as intact packages into the extracellular space. These *extracellular vesicles* often carry larger molecules (e.g., proteins, RNA molecules) between different neurons and glia in the central nervous system (see Holm, Kaiser, & Schwab, 2018; Paolicelli, Bergamini, & Rajendran, 2018). Some of these transmitted molecules can induce persistent changes in the expression of genes through epigenetic mechanisms (see Bakhshandeh, Kamaleddin, & Aalishah, 2017).

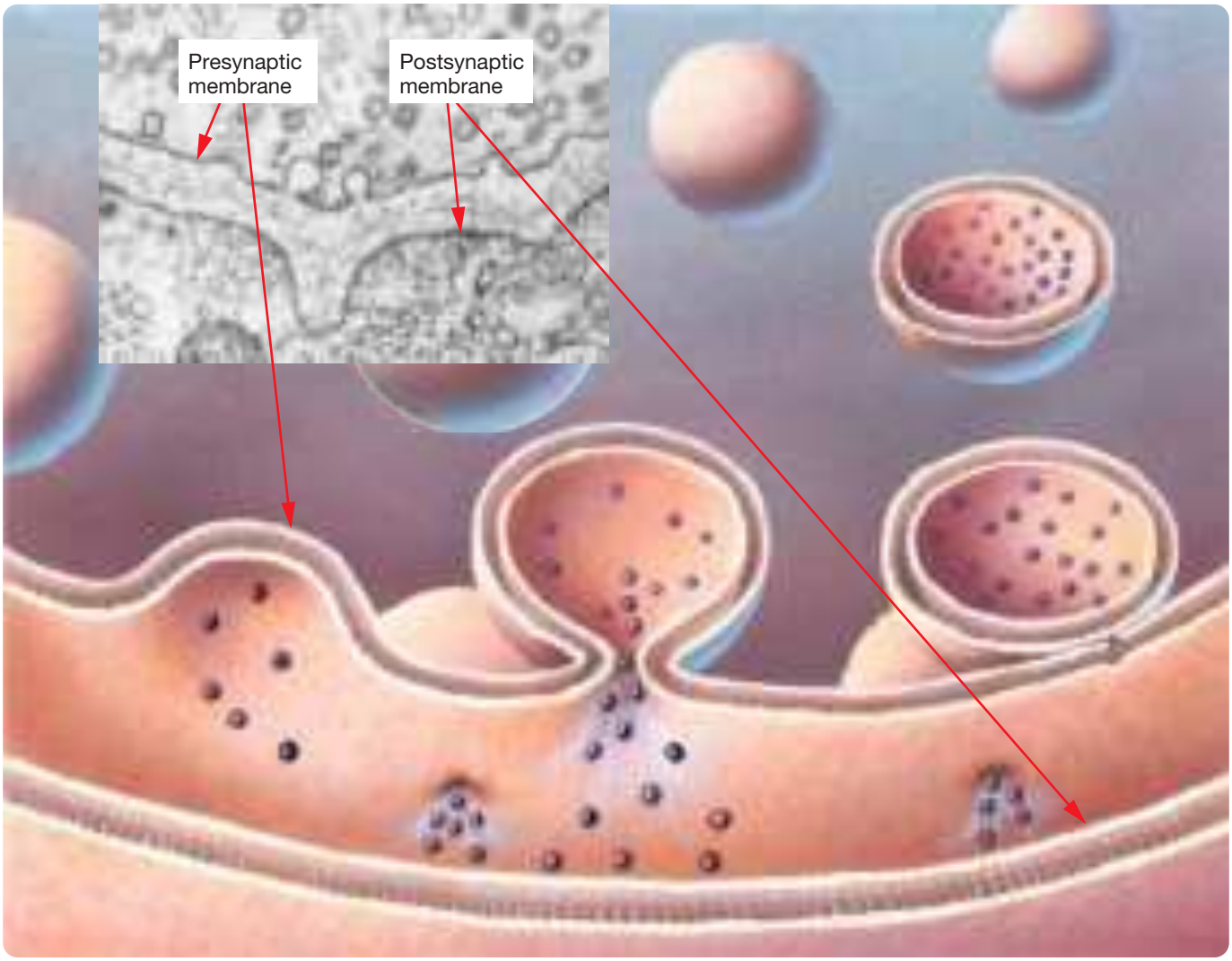
Activation of Receptors by Neurotransmitter Molecules

LO 4.12 Describe the differences between ionotropic and metabotropic receptors.

Once released, neurotransmitter molecules produce signals in postsynaptic neurons by binding to **receptors** in the postsynaptic membrane. Each receptor is a protein that contains binding sites for only particular neurotransmitters; thus, a neurotransmitter can influence only those cells that have receptors for it. Any molecule that binds to another is referred to as its **ligand**, and a neurotransmitter is thus said to be a ligand of its receptor.

It was initially assumed that there is only one type of receptor for each neurotransmitter, but this has not proved to be the case. As more receptors have been identified, it has become clear that most neurotransmitters bind to several different types of receptors. The different types of receptors to which a particular neurotransmitter can bind are called the **receptor subtypes** for that neurotransmitter. The various receptor subtypes for a neurotransmitter are typically located in different brain areas, and they typically respond to the neurotransmitter in different ways.

Figure 4.10 Schematic illustration of exocytosis.



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Thus, one advantage of receptor subtypes is that they enable one neurotransmitter to transmit different kinds of messages to different parts of the brain.

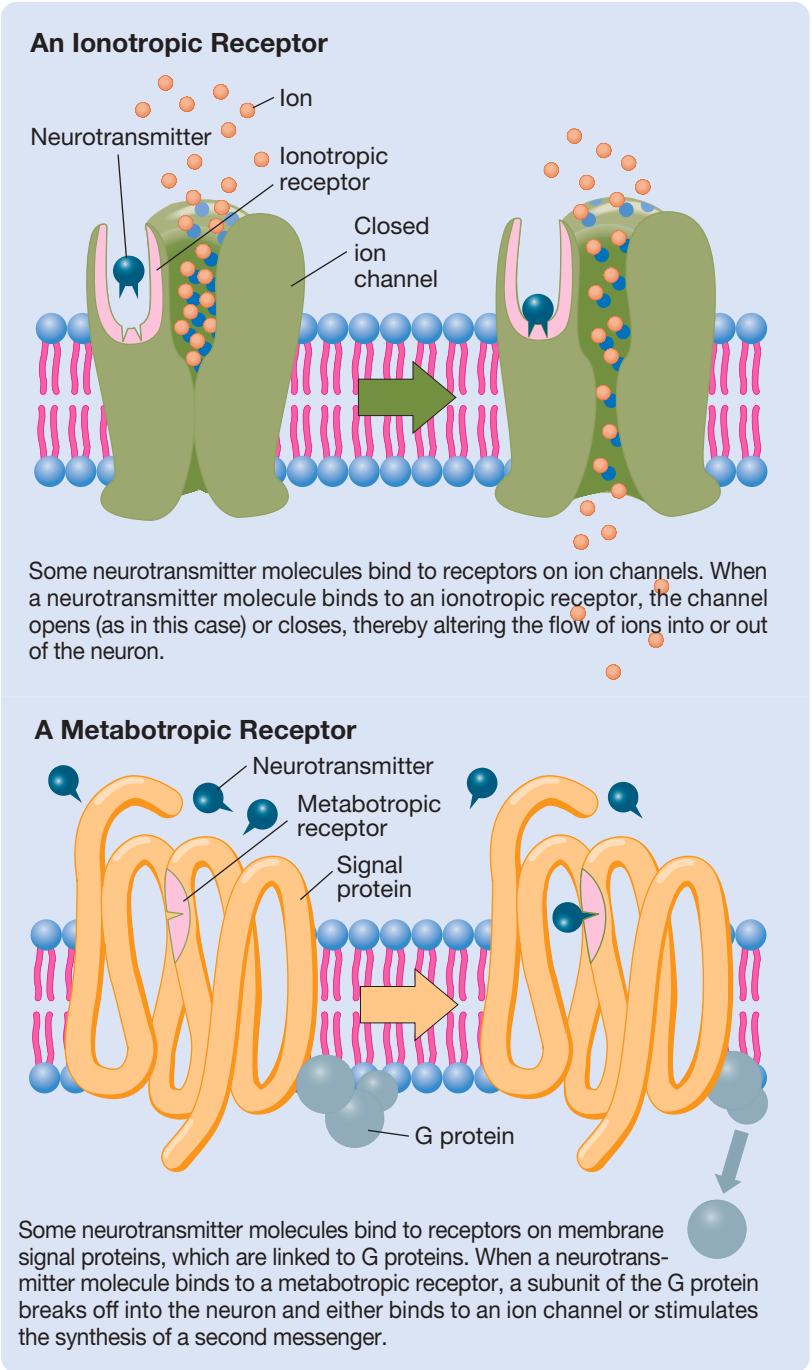
The binding of a neurotransmitter to one of its receptor subtypes can influence a postsynaptic neuron in one of two fundamentally different ways, depending on whether the receptor is ionotropic or metabotropic. **Ionotropic receptors** are associated with ligand-activated ion channels; **metabotropic receptors** are typically associated with signal proteins and **G proteins** (*guanosine-triphosphate–sensitive proteins*); see Figure 4.11.

When a neurotransmitter molecule binds to an ionotropic receptor, the associated ion channel usually opens or closes immediately, thereby inducing an immediate postsynaptic potential. For example, in some neurons, EPSPs (depolarizations) occur because the neurotransmitter opens sodium channels, thereby increasing the flow of Na^+ ions into the neuron. In contrast, IPSPs (hyperpolarizations) often occur because the neurotransmitter opens potassium channels or chloride (Cl^-) channels, thereby increasing the flow of K^+ ions out of the neuron or the flow of Cl^- ions into it, respectively.

Metabotropic receptors are more prevalent than ionotropic receptors, and their effects are slower to develop, longer-lasting, more diffuse, and more varied. There are many different kinds of metabotropic receptors, but each is attached to a serpentine signal protein that winds its way back and forth through the cell membrane seven times. The metabotropic receptor is attached to a portion of the signal protein outside the neuron; the G protein is attached to a portion of the signal protein inside the neuron.

When a neurotransmitter binds to a metabotropic receptor, a subunit of the associated G protein breaks away. Then, one of two things happen, depending on the particular G protein. The subunit may move along the inside surface of the membrane and bind to a nearby ion channel, thereby inducing an EPSP or IPSP; or it may trigger the synthesis of a chemical called a **second messenger** (neurotransmitters are considered to be the *first messengers*). Once created, a second messenger diffuses through the cytoplasm and

Figure 4.11 Ionotropic and metabotropic receptors.



may influence the activities of the neuron in a variety of ways (Lyon, Taylor, & Tesmer, 2014)—for example, it may enter the nucleus and bind to the DNA, thereby influencing genetic expression. Thus, a neurotransmitter's binding to a metabotropic receptor can have radical, long-lasting effects. Furthermore, there is now evidence that ionotropic receptors can also produce second messengers that can have enduring effects (see Valbuena & Lerma, 2016; Reiner & Levitz, 2018).

Epigenetic mechanisms (see Chapter 2) that act on both ionotropic and metabotropic receptors are of increasing interest to researchers. For example, there is strong evidence that the structures of both types of receptors (and thus their functionality) can be altered through epigenetic mechanisms (see Fomsgaard et al., 2018). Moreover, certain disorders may be the result of modifications to receptor structure via epigenetic mechanisms (see Matosin et al., 2017).

One type of metabotropic receptor—autoreceptors—warrants special mention. **Autoreceptors** are metabotropic receptors that have two unconventional characteristics: They bind to their neuron's own neurotransmitter molecules, and they are located on the presynaptic, rather than the postsynaptic, membrane. Their usual function is to monitor the number of neurotransmitter molecules in the synapse, to reduce subsequent release when the levels are high, and to increase subsequent release when they are low.

Differences between small-molecule and peptide neurotransmitters in patterns of release and receptor binding suggest that they serve different functions. Small-molecule neurotransmitters tend to be released into directed synapses and to activate either ionotropic receptors or metabotropic receptors that act directly on ion channels. In contrast, neuropeptides tend to be released diffusely, and virtually all bind to metabotropic receptors that act through second messengers. Consequently, the function of small-molecule neurotransmitters appears to be the transmission of rapid, brief excitatory or inhibitory signals to adjacent cells; and the function of neuropeptides appears to be the transmission of slow, diffuse, long-lasting signals.

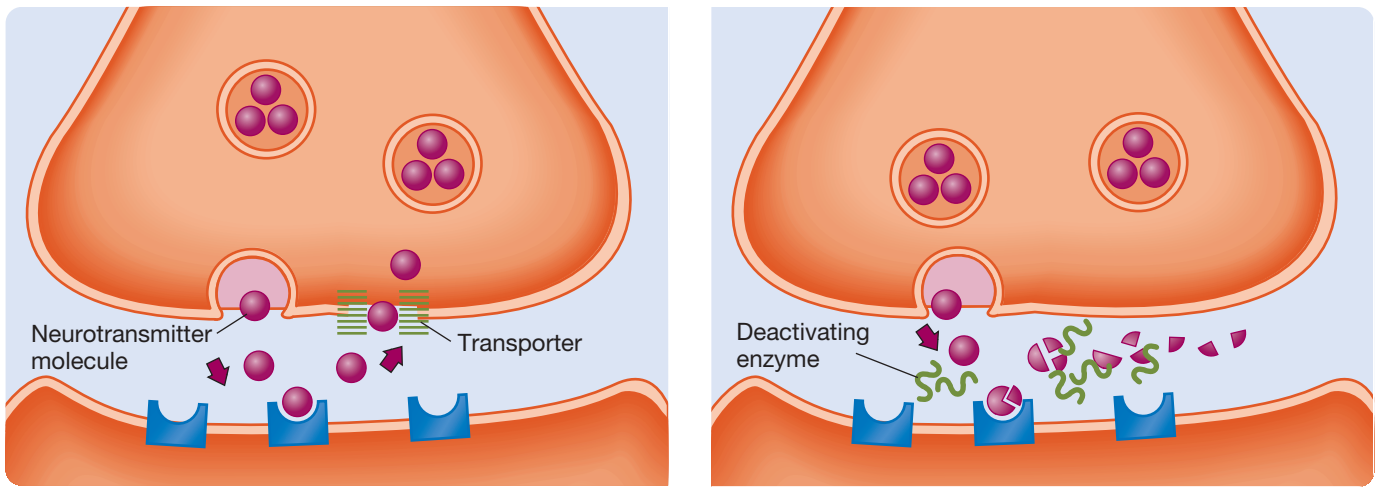
Reuptake, Enzymatic Degradation, and Recycling

LO 4.13 Explain how neurotransmitters are removed from a synapse.

If nothing intervened, a neurotransmitter molecule would remain active in the synapse, in effect clogging that channel of communication. However, two mechanisms terminate synaptic messages and keep that from happening. These two message-terminating mechanisms are **reuptake** by transporters and **enzymatic degradation** (see Figure 4.12).

Reuptake is the more common of the two deactivating mechanisms. The majority of neurotransmitters, once

Figure 4.12 The two mechanisms for terminating neurotransmitter action in the synapse: reuptake and enzymatic degradation.



released, are almost immediately drawn back into the presynaptic buttons by transporter mechanisms.

In contrast, other neurotransmitters are degraded (broken apart) in the synapse by the action of **enzymes**—proteins that stimulate or inhibit biochemical reactions without being affected by them. For example, *acetylcholine*, one of the few neurotransmitters for which enzymatic degradation is the main mechanism of synaptic deactivation, is broken down by the enzyme **acetylcholinesterase**.

Terminal buttons are models of efficiency. Once released, neurotransmitter molecules or their breakdown products are drawn back into the button and recycled, regardless of the mechanism of their deactivation. Even the vesicles, once they have done their job, are drawn back into the neuron from the presynaptic membrane and are used to create new vesicles (see Soykan, Maritzen, & Haucke, 2016).

Glia, Gap Junctions, and Synaptic Transmission

LO 4.14 Describe the roles of glia and gap junctions in synaptic transmission.

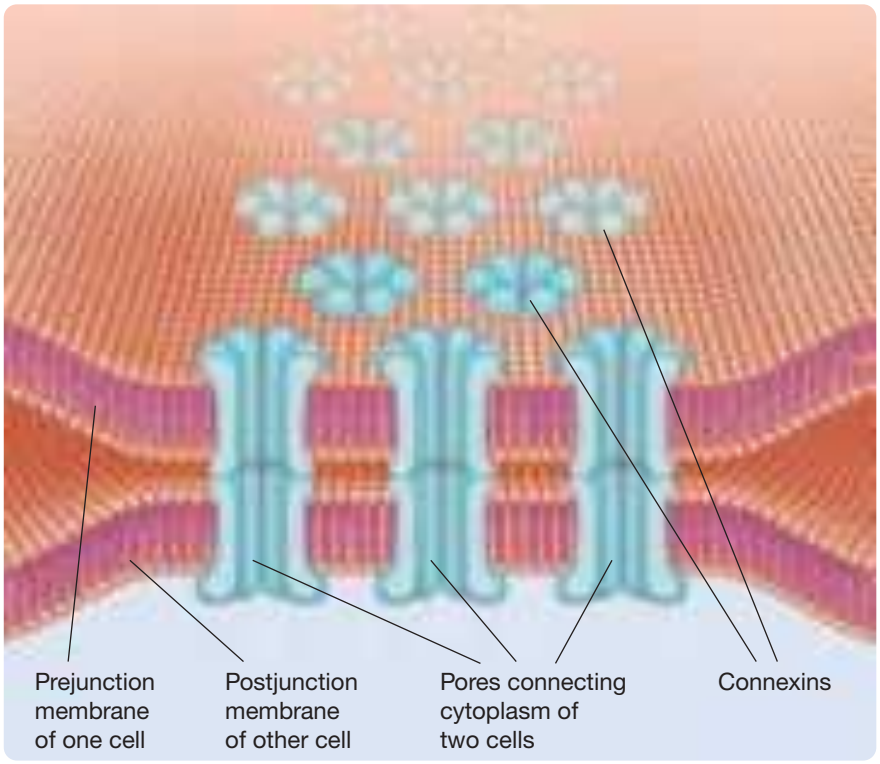
Glial cells, once overlooked as playing merely supportive roles in the nervous system, have been thrust to center stage by a wave of remarkable findings. For example, astrocytes have been shown to release chemical transmitters, to contain receptors for neurotransmitters, to conduct signals, and to influence synaptic transmission between neurons (see Bazargani & Attwell, 2016; Martín et al., 2015). Indeed, it is now inappropriate to think of brain function solely in terms of neuron–neuron connections. Neurons are only part of the story. Will *neuroscience* prove to be a misnomer? Anybody for "gliascience"?

The explosion of interest in the role of glial cells in brain function has gone hand in hand with an increased interest in the role of gap junctions. **Gap junctions** are narrow spaces between adjacent cells that are bridged by fine, tubular, cytoplasm-filled protein channels, called *connexins*. Consequently, gap junctions connect the cytoplasm of two adjacent cells, allowing electrical signals and small molecules (e.g., second messengers) to pass from one cell to the next (see Figure 4.13). Gap junctions are responsible for the existence of *electrical synapses*, which can transmit signals much more rapidly than chemical synapses (see Coulon & Landisman, 2017).

The presence of gap junctions between adjacent neurons was first reported in the 1950s, but because the first studies were limited to invertebrates and simple vertebrates, gap junction-mediated communication between neurons was assumed to be of little significance in the mammalian brain. Even after the presence of gap junctions was established in mammalian (i.e., rodent) brains in the early 1970s, the idea that gap junctions could play a major role in human brain function was not widely entertained. Then in the 1990s, stimulated by several important technical developments and the identification of the gap junction gene, gap junctions became the focus of neuroscientific research (see McCracken & Roberts, 2006). It is now firmly established that glial cells and gap junctions play major roles in brain function (see Rusakov et al., 2014; Coulon & Landisman, 2017; Szczupak, 2016).

The principles according to which astrocytes and gap junctions are distributed in the mammalian brain provide some of the best clues about their function. First, let's consider cerebral gap junctions. Cerebral gap junctions occur between all classes of cerebral cells; however, the majority of them seem to occur between cells of the same kind. For example, many gap junctions link astrocytes together

Figure 4.13 Gap junctions connect the cytoplasm of two adjacent cells. In the mammalian brain, there are many gap junctions between glial cells, between neurons, and between neurons and glia cells.



into networks of glial cells. Also, gap junctions between neurons are particularly prevalent between inhibitory interneurons of the same type (e.g., Lee et al., 2014). Accordingly, one function of gap junctions appears to be to synchronize the activities of like cells in a particular area.

One aspect of astrocytic organization suggests that they too play a role of synchronizing activities of like cells in a particular area. Unlike neurons, astrocytes are distributed evenly throughout a particular area, with only one astrocyte per location and little overlap between the projections of adjacent astrocytes. This suggests that each astrocyte coordinates the activity of neurons in its domain, and with as many as 40,000 processes, each astrocyte has a great potential to coordinate activity (see Pannasch & Rouach, 2013). Gap junctions on astrocytes tend to occur at the end of each process, where it comes in contact with processes from adjacent astrocytes.

Scan Your Brain

Before moving on to the discussion of specific neurotransmitters, review the general principles of axon conduction and synaptic transmission. Draw a line to connect each term in the left column with the appropriate word or phrase in the right column. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. fatty
2. sclerosis
3. cell bodies
4. nondecremental
5. presynaptic facilitation
6. nondirected synapses
7. synaptic vesicles
8. from cell body to terminal buttons
9. acetylcholinesterase
10. short amino acid chains
11. saltatory
12. metabotropic receptors
13. electrical synapses
14. spines

a. axonal conduction of action potentials
b. orthodromic
c. myelin
d. nodes of Ranvier
e. multiple
f. dendritic
g. somas
h. axoaxonic synapses
i. string-of-beads
j. neuropeptides
k. store neurotransmitters
l. G proteins
m. enzymatic degradation
n. gap junctions

Scan Your Brain answers: (1) c, (2) e, (3) g, (4) a, (5) h, (6) i, (7) k, (8) b, (9) m, (10) j, (11) d, (12) l, (13) n, (14) f.

Neurotransmitters

Now that you understand the basics of neurotransmitter function, let's take a closer look at a select few of the well over 100 neurotransmitters that have been identified.

Overview of the Neurotransmitter Classes

LO 4.15 Name the major classes of neurotransmitters.

The following are three classes of conventional small-molecule neurotransmitters: the *amino acids*, the *monoamines*, and *acetylcholine*. A fourth group of various small-molecule neurotransmitters are often referred to as *unconventional neurotransmitters* because their mechanisms of action are unusual. In contrast to the small-molecule neurotransmitters, there is only one class of large-molecule neurotransmitters: the *neuropeptides*. All of the neurotransmitter classes and individual neurotransmitters that appear in this module in boldface type are summarized in Figure 4.16 at the end of this module.

The Roles and Functions of Neurotransmitters

LO 4.16 Identify the class, and discuss at least one function, of each of the neurotransmitters discussed in this section.

In this section, we examine some of the many neurotransmitters that enable intercellular communication within our nervous system. This section is organized according to the four classes of neurotransmitters discussed in the previous section.

AMINO ACID NEUROTRANSMITTERS. The neurotransmitters in the vast majority of fast-acting, directed synapses in the central nervous system are amino acids—the molecular building blocks of proteins. The four most widely studied **amino acid neurotransmitters** are **glutamate**, **aspartate**, **glycine**, and **gamma-aminobutyric acid (GABA)**. The first three are common in the proteins we consume, whereas GABA is synthesized by a simple modification of the structure of glutamate. Glutamate is the most prevalent excitatory neurotransmitter in the mammalian central nervous system. GABA is the most prevalent inhibitory neurotransmitter; however, it has excitatory effects at some synapses (see Watanabe, Fukuda, & Nabekura, 2014).

MONOAMINE NEUROTRANSMITTERS. Monoamines are another class of small-molecule neurotransmitters. Each is synthesized from a single amino acid—hence the name *monoamine* (one amine). **Monoamine neurotransmitters** are slightly larger than amino acid neurotransmitters, and their effects tend to be more diffuse. The monoamines are present in small groups of neurons whose cell bodies are, for the most part, located in the brain stem. These neurons often have highly branched axons with many varicosities (string-of-beads synapses), from which monoamine neurotransmitters are diffusely released into the extracellular fluid (see Figures 4.9 and 4.14).

There are four monoamine neurotransmitters: **dopamine**, **epinephrine**, **norepinephrine**, and **serotonin**. They are subdivided into two groups, **catecholamines** and **indolamines**, on the basis of their structures. Dopamine, norepinephrine, and epinephrine are catecholamines. Each is synthesized from the amino acid *tyrosine*. Tyrosine is converted to *L-dopa*, which in turn is converted to dopamine. Neurons that release norepinephrine have an extra enzyme (one that is not present in dopaminergic neurons), which converts the dopamine in them to norepinephrine. Similarly, neurons that release epinephrine have all the enzymes present in neurons that release norepinephrine, along with an extra enzyme that converts norepinephrine to epinephrine (see Figure 4.15). In contrast to the other monoamines, serotonin (also called *5-hydroxytryptamine*, or *5-HT*) is synthesized from the amino acid *tryptophan* and is classified as an indolamine.

Neurons that release norepinephrine are called *noradrenergic*; those that release epinephrine are called *adrenergic*. There are two reasons for this naming. One is that epinephrine and norepinephrine used to be called *adrenaline* and *noradrenaline*, respectively, by many scientists, until a drug company registered *Adrenalin* as a brand name. The other reason will become apparent if you try to say *norepinephrinergic*.

ACETYLCHOLINE. **Acetylcholine** (abbreviated *Ach*) is a small-molecule neurotransmitter that is, in one major respect, like a professor who is late for a lecture: It is in a class by itself. It is created by adding an *acetyl* group to a *choline* molecule. Acetylcholine is the neurotransmitter at neuromuscular junctions, at many of the synapses in the autonomic nervous system, and at synapses in several parts of the central nervous system. Recall that acetylcholine is broken down in the synapse by the enzyme *acetylcholinesterase*. Neurons that release acetylcholine are said to be *cholinergic*.

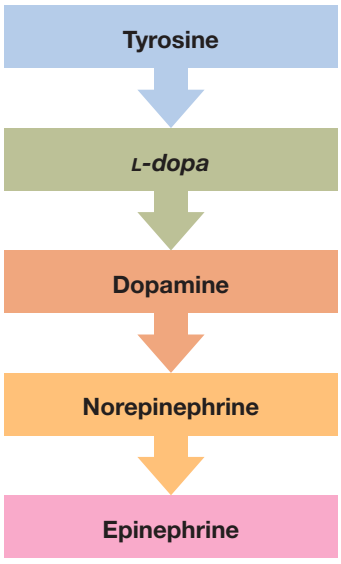
UNCONVENTIONAL NEUROTRANSMITTERS. The unconventional neurotransmitters act in ways that are

Figure 4.14 String-of-beads noradrenergic nerve fibers. The bright, beaded structures represent sites in these axons where the monoamine neurotransmitter norepinephrine is stored and released into the surrounding extracellular fluid.

Dr. David Jacobwitz/SCIENCE PHOTO LIBRARY/Getty Images

different from those that neuroscientists have come to think of as typical for such substances. One class of unconventional neurotransmitters, the **soluble-gas neurotransmitters**, includes **nitric oxide** and **carbon monoxide**. These neurotransmitters are produced in the neural cytoplasm and immediately diffuse through the cell membrane into the extracellular fluid and then into nearby cells. They easily pass through cell membranes because they are soluble in lipids. Once inside another cell, they stimulate the production of a second messenger and in a few seconds are deactivated by being converted to other molecules. They are difficult to study because they exist for only a few seconds.

Figure 4.15 The steps in the synthesis of catecholamines from tyrosine.



Soluble-gas neurotransmitters have been shown to be involved in *retrograde transmission*. At some synapses, they transmit feedback signals from the postsynaptic neuron back to the presynaptic neuron. The function of retrograde transmission seems to be to regulate the activity of presynaptic neurons (see Iremonger, Wamsteeker Cusulin, & Bains, 2013).

Another class of unconventional neurotransmitters is the endocannabinoids. **Endocannabinoids** are neurotransmitters that are similar to *delta-9-tetrahydrocannabinol* (THC), the main *psychoactive* (producing psychological effects) constituent of marijuana. So far, two endocannabinoids have been discovered (see Di Marzo, Stella, & Zimmer, 2015). The most widely studied is **anandamide** (from the Sanskrit word *ananda*, which means "eternal bliss"). Like the soluble gases, the endocannabinoids are produced immediately before they are released. Endocannabinoids are synthesized from fatty compounds in the cell membrane; they tend to be released from the dendrites and cell body; and they tend to have most of their effects on presynaptic neurons, inhibiting subsequent synaptic

transmission (see Ohno-Shosaku & Kano, 2014; Younts & Castillo, 2014).

NEUROPEPTIDES. About 100 neuropeptides have been identified. The actions of each neuropeptide depend on its amino acid sequence.

It is usual to loosely group **neuropeptide transmitters** into five categories. Three of these categories acknowledge that neuropeptides often function in multiple capacities, not just as neurotransmitters: One category (**pituitary peptides**) contains neuropeptides that were first identified as hormones released by the pituitary; a second category (**hypothalamic peptides**) contains neuropeptides that were first identified as hormones released by the hypothalamus; and a third category (**brain–gut peptides**) contains neuropeptides that were first discovered in the gut. The fourth category (**opioid peptides**) contains neuropeptides that are similar in structure to the active ingredients of opium, and the fifth (**miscellaneous peptides**) is a catch-all category that contains all of the neuropeptide transmitters that do not fit into one of the other four categories.

Figure 4.16 summarizes all the neurotransmitters that were introduced in this module. If it has not already occurred to you, this table should be very useful for reviewing the material in this module.

Pharmacology of Synaptic Transmission and Behavior

In case you have forgotten, the reason we have asked you to invest so much effort in learning about the neurotransmitters is that they play a key role in how the brain works. This chapter began on a behavioral note by considering the pathological behavior of Roberto Garcia d'Orta, which resulted from a Parkinson's disease-related disruption of his dopamine function. Now, let's return to behavior.

Most of the methods that biopsychologists use to study the behavioral effects of neurotransmitters are *pharmacological* (involving drugs). To study neurotransmitters and behavior, researchers administer to human or nonhuman subjects drugs that have particular effects on particular neurotransmitters and then assess the effects of the drugs on behavior.

Drugs have two fundamentally different kinds of effects on synaptic transmission: They facilitate it or they inhibit it. Drugs that facilitate the effects of a particular neurotransmitter are said to be **agonists** of that neurotransmitter. Drugs that inhibit the effects of a particular neurotransmitter are said to be its **antagonists**.

Figure 4.16 Classes of neurotransmitters and the particular neurotransmitters that were discussed (and appeared in boldface) in this module.

Small-Molecule Neurotransmitters

Amino acids		Glutamate Aspartate Glycine GABA
Monoamines	Catecholamines	Dopamine Epinephrine Norepinephrine
	Indolamines	Serotonin
Acetylcholine		Acetylcholine
Unconventional neurotransmitters	Soluble gases	Nitric oxide Carbon monoxide
	Endocannabinoids	Anandamide

Large-Molecule Neurotransmitters

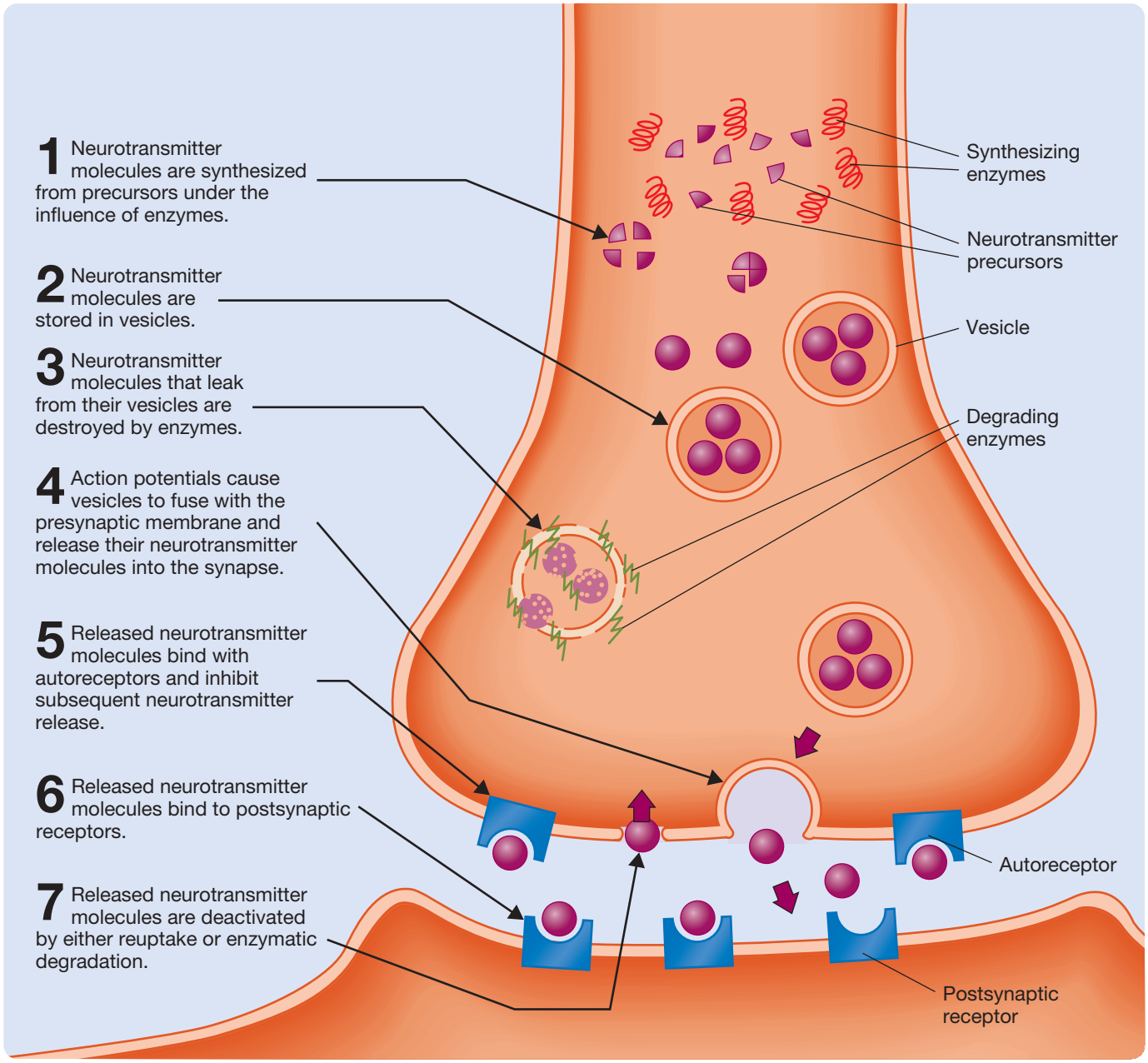
Neuropeptides	Pituitary peptides Hypothalamic peptides Brain–gut peptides Opioid peptides Miscellaneous peptides

How Drugs Influence Synaptic Transmission

LO 4.17 Provide a general overview of how drugs influence synaptic transmission.

Although synthesis, release, and action vary from neurotransmitter to neurotransmitter, the following seven general steps are common to most neurotransmitters: (1) synthesis of the neurotransmitter, (2) storage in vesicles, (3) breakdown in the cytoplasm of any neurotransmitter that leaks from the vesicles, (4) exocytosis, (5) inhibitory feedback via autoreceptors, (6) activation of postsynaptic receptors, and (7) deactivation. Figure 4.17 illustrates these seven steps, and Figure 4.18 illustrates some ways that agonistic and antagonistic drugs influence them. For example, some agonists of a particular neurotransmitter bind to postsynaptic

Figure 4.17 Seven steps in neurotransmitter action: (1) synthesis, (2) storage in vesicles, (3) breakdown of any neurotransmitter leaking from the vesicles, (4) exocytosis, (5) inhibitory feedback via autoreceptors, (6) activation of postsynaptic receptors, and (7) deactivation.



receptors and activate them, whereas some antagonistic drugs, called **receptor blockers**, bind to postsynaptic receptors without activating them and, in so doing, block the access of the usual neurotransmitter.

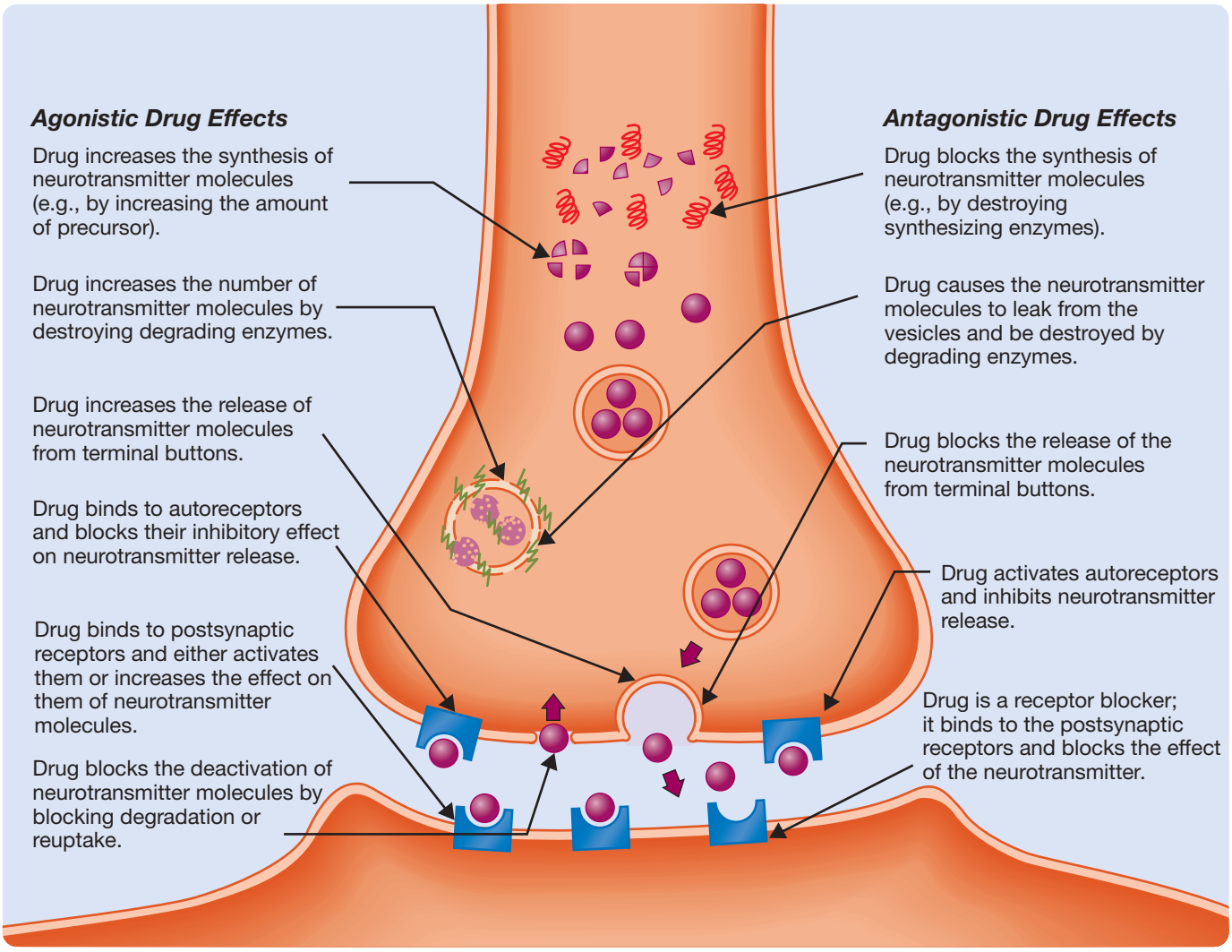
Behavioral Pharmacology: Three Influential Lines of Research

LO 4.18 Describe three examples of how drugs have been used to influence neurotransmission.

You will encounter discussions of the *putative* (hypothetical) behavioral functions of various neurotransmitters in subsequent chapters. However, this chapter ends with descriptions of three particularly influential lines of research on neurotransmitters and behavior. Each line of research led to the discovery of an important principle of neurotransmitter function, and each illustrates how drugs are used to study the nervous system and behavior.

WRINKLES AND DARTS: DISCOVERY OF RECEPTOR SUBTYPES. It was originally assumed that there was one kind of receptor for each neurotransmitter, but this notion was dispelled by research on acetylcholine receptors (see Changeux, 2013; Papke, 2014). Some acetylcholine receptors bind to *nicotine* (a CNS stimulant and the major

Figure 4.18 Some mechanisms of agonistic and antagonistic drug effects.



psychoactive ingredient of tobacco), whereas other acetylcholine receptors bind to *muscarine* (a poisonous substance found in some mushrooms). These two kinds of acetylcholine receptors thus became known as *nicotinic receptors* and *muscarinic receptors*.

Next, it was discovered that nicotinic and muscarinic receptors are distributed differently in the nervous system, have different modes of action, and consequently have different behavioral effects. Both nicotinic and muscarinic receptors are found in the CNS and the PNS. In the PNS, many nicotinic receptors occur at the junctions between motor neurons and muscle fibers, whereas many muscarinic receptors are located in the autonomic nervous system (ANS). Nicotinic and muscarinic receptors are ionotropic and metabotropic, respectively.

Many of the drugs used in research and medicine are extracts of plants that have long been used for medicinal and recreational purposes. The cholinergic agonists and antagonists illustrate this point well. For example, the ancient Greeks consumed extracts of the belladonna plant to treat stomach ailments and to make themselves more attractive. Greek women believed that the pupil-dilating effects of these extracts enhanced their beauty (*belladonna* means "beautiful lady"). **Atropine**, which is the main active ingredient of belladonna, is a receptor blocker that exerts its antagonist effect by binding to muscarinic receptors, thereby blocking the effects of acetylcholine on them. The pupil-dilating effects of atropine are mediated by its antagonist actions on muscarinic receptors in the ANS. In contrast, the disruptive effects of large doses of atropine on memory are mediated by its antagonistic effect on muscarinic receptors in the CNS. The disruptive effect of high doses of atropine on memory was one of the earliest clues that cholinergic mechanisms may play a role in memory (see Chapter 11).

South Americans have long used *curare*—an extract of a certain class of woody vines—on the tips of darts they use to kill their game. Like atropine, curare is a receptor blocker

at cholinergic synapses, but it acts at nicotinic receptors. By binding to nicotinic receptors, curare blocks transmission at neuromuscular junctions, thus paralyzing its recipients and killing them by blocking their respiration. You may be surprised, then, to learn that the active ingredient of curare is sometimes administered to human patients during surgery to ensure that their muscles do not contract during an incision. When curare is used for this purpose, the patient's breathing must be artificially maintained by a respirator.

Botox (short for *Botulinium toxin*), a neurotoxin released by a bacterium often found in spoiled food, is another nicotinic antagonist, but its mechanism of action is different: It blocks the release of acetylcholine at neuromuscular junctions and is thus a deadly poison. However, injected in minute doses at specific sites, it has applications in medicine (e.g., reduction of tremors) and cosmetics (e.g., reduction of wrinkles; see Figure 4.19).

PLEASURE AND PAIN: DISCOVERY OF ENDOGENOUS OPIOIDS. Opium, the sticky resin obtained from the seed pods of the opium poppy, has been used by humans since prehistoric times for its pleasurable effects. Morphine, its major psychoactive ingredient, is addictive. But morphine also has its good side: It is an effective *analgesic* (painkiller)—see Chapters 7 and 15.

In the 1970s, it was discovered that opioid drugs such as morphine bind effectively to receptors in the brain. These receptors were generally found in the hypothalamus and other limbic areas, but they were most concentrated in the area of the brain stem around the cerebral aqueduct, which connects the third and fourth ventricles; this part of the brain stem is called the **periaqueductal gray (PAG)**. Microinjection of morphine into the PAG, or even electrical stimulation of the PAG, produces strong analgesia.

Figure 4.19 Receiving cosmetic Botox injections.

Viacheslav Iakobchuk/Alamy Stock Photo

The existence of selective opioid receptors in the brain raised an interesting question: Why are they there? They are certainly not there so that once humans discovered opium, opioids would have a place to bind. The existence of opioid receptors suggested that *opioid* chemicals occur naturally in the brain, and that possibility triggered an intensive search for them.

Several families of **endogenous** (occurring naturally within the body) opioids have been discovered. First discovered were the **enkephalins** (meaning "in the head"). Another major family of endogenous opioids are the **endorphins** (a contraction of "endogenous morphine"). All endogenous opioid neurotransmitters are neuropeptides, and their receptors are metabotropic.

TREMORS AND MENTAL ILLNESS: DISCOVERY OF ANTIPSYCHOTIC DRUGS. Arguably, the most important event in the treatment of mental illness has been the development of drugs for the treatment of schizophrenia. Surprisingly, Parkinson's disease, the disease from which Roberto Garcia d'Orta suffered, played a major role in their discovery.

In the 1950s, largely by chance, two drugs were found to have antipsychotic effects; that is, they reduced the severity of psychosis—the major symptom of schizophrenia. Although these two drugs were not related structurally, they both produced a curious pattern of effects: Neither drug appeared to have any antipsychotic activity until patients had been taking it for about 3 weeks, at which point the drug also started to produce mild Parkinsonian symptoms (e.g., tremor-at-rest). Researchers put this result together with two other findings: (1) Parkinson's disease is associated with the degeneration of a main *dopamine* pathway in the brain, and (2) dopamine agonists (e.g., *cocaine* and *amphetamines*) produce a transient condition that resembles schizophrenia. Together, these findings suggested that schizophrenia might be caused by excessive activity at dopamine synapses and thus that potent dopamine antagonists would be effective in its treatment.

Journal Prompt 4.3

Why do biopsychologists need a solid understanding of neural conduction and synaptic transmission?

It would be a mistake to think that antipsychotic drugs cure schizophrenia or that they help in every case. However, they help improve the quality of life of many individuals with schizophrenia. You will learn much more about this important line of research in Chapter 18.

Themes Revisited

The function of the nervous system, like the function of any circuit, depends on how signals travel through it. The primary purpose of this chapter was to introduce you to neural conduction and synaptic transmission. This introduction touched on four of the text's five main themes.

The clinical implications theme was illustrated by the opening case of the Lizard, Roberto Garcia d'Orta. Then this theme was picked up again at the end of the chapter during discussions of curare, Botox, endogenous opioids, and antipsychotic drugs.

The thinking creatively theme arose in four metaphors: the social network metaphor of neural network communication, the ripples-on-the-pond metaphor of the summation of PSPs, the firing-gun metaphor of action potentials, and the mouse-traps-on-a-wobbly-shelf metaphor of axonal conduction. Metaphors are useful in teaching, and scientists find them useful for thinking about the phenomena they study.

Finally, the evolutionary perspective theme was implicit throughout the entire chapter because almost all neurophysiological research is conducted on the neurons and synapses of nonhuman subjects.

We also caught a glimpse of one of our two emerging themes in this chapter: thinking about epigenetics. In particular, this theme arose in the context of extracellular vesicles and ionotropic and metabotropic receptors.

Key Terms

Resting Membrane Potential

Membrane potential, p. 99
Microelectrodes, p. 99
Resting potential, p. 99
Polarized, p. 99
Ions, p. 99
Ion channels, p. 99
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Chapter 5

The Research Methods of Biopsychology

Understanding What Biopsychologists Do

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Chapter Overview and Learning Objectives

PART ONE Methods of Studying the Nervous System

Methods of Visualizing and Stimulating the Living Human Brain	**LO 5.1**	Describe two x-ray-based techniques for visualizing the living human brain.
	LO 5.2	Describe the positron emission tomography (PET) technique.
	LO 5.3	Describe three magnetic-field-based techniques for imaging the living human brain.
	LO 5.4	Describe an ultrasound-based technique for imaging the living human brain.
	LO 5.5	Describe three transcranial stimulation techniques.
Recording Human Psychophysiological Activity	**LO 5.6**	Describe two psychophysiological measures of brain activity.
	LO 5.7	Describe two psychophysiological measures of somatic nervous system activity.

	LO 5.8 Describe two psychophysiological measures of autonomic nervous system activity.
Invasive Physiological Research Methods	**LO 5.9** Describe the process of stereotaxic surgery. **LO 5.10** Describe four types of lesion methods and explain why it is important to be cautious when interpreting the effects of lesions. **LO 5.11** Describe the technique of electrical brain stimulation. **LO 5.12** Describe four invasive electrophysiological recording methods.
Pharmacological Research Methods	**LO 5.13** Describe the various methods of drug administration. **LO 5.14** Describe the method of selective neurotoxic lesions. **LO 5.15** Describe two techniques for measuring chemical activity in the brain. **LO 5.16** Describe two techniques for locating particular neurotransmitters or receptors in the brain.
Genetic Methods	**LO 5.17** Explain the gene knockout technique by describing an experiment that employed the technique. **LO 5.18** Explain the gene knockin technique by describing an experiment that employed the technique. **LO 5.19** Describe how modern gene-editing techniques, such as the CRISP-Cas9 method, can provide better ways of assessing the role of a gene in behavior. **LO 5.20** Explain how green fluorescent protein has been used as a research tool in the neurosciences. **LO 5.21** Explain how opsins have been used as a research tool in the neurosciences.

PART TWO Behavioral Research Methods of Biopsychology

Neuropsychological Testing	**LO 5.22** Describe three approaches to neuropsychological testing. **LO 5.23** Describe those tests that are often administered as part of an initial common neuropsychological test battery. **LO 5.24** Describe tests that might be used by a neuropsychologist to investigate in more depth general problems revealed by a common neuropsychological test battery.
Behavioral Methods of Cognitive Neuroscience	**LO 5.25** Describe the paired-image subtraction technique. **LO 5.26** Understand the default mode network and know the structures that are part of that network. **LO 5.27** Explain what a mean difference image is. **LO 5.28** Explain the concept of functional connectivity.

Biopsychological Paradigms of Animal Behavior

LO 5.29 Describe three behavioral paradigms used to study species-common behaviors.

LO 5.30 Describe the Pavlovian conditioning paradigm and the operant conditioning paradigm.

LO 5.31 Describe four seminatural animal learning paradigms.

LO 5.32 Explain why multiple techniques should be used when trying to answer a specific question.

The Ironic Case of Professor P.

Two weeks before his brain surgery, Professor P. reported to the hospital for a series of tests. What amazed Professor P. most about these tests was how familiar they seemed. No, Professor P. was not a psychic; he was a biopsychologist, and he was struck by how similar the tests performed on him were to the tests he had encountered in his work.

Professor P. had a brain tumor on his right auditory-vestibular cranial nerve (cranial nerve VIII; see Appendices III and IV), and he had to have it *excised* (cut out). First, Professor P.'s auditory abilities were assessed by measuring his ability to detect sounds of various volumes and pitches and then by measuring the magnitude of the EEG signals evoked in his auditory cortex by clicks in his right ear.

Next, Professor P.'s vestibular function (balance) was tested by injecting cold water into his ear.

"Do you feel anything, Professor P.?"

"Well, a cold ear."

"Nothing else?"

"No."

So colder and colder water was tried with no effect until the final, coldest test was conducted. "Ah, that feels weird," said Professor P. "It's kind of like the bed is tipping."

The results of the tests were bad, or good, depending on your perspective—they certainly revealed his deficits. Professor P.'s hearing in his right ear was poor, and his right vestibular nerve was barely functioning. "At the temperatures we flushed down there, most people would have been on their hands and knees puking their guts out," said the medical technician. Professor P. smiled at her technical terminology.

Of course, he was upset that his brain had deteriorated so badly, but he sensed that his neurosurgeon was secretly pleased: "We won't have to try to save the nerve; we'll just cut it."

There was one last test. The skin of his right cheek was lightly pricked while the EEG responses of his somatosensory cortex were recorded from his scalp. "This is just to establish a baseline for the surgery," it was explained. "One main risk of removing tumors on the auditory-vestibular cranial nerve (VIII) is damaging the facial cranial nerve (VII), and that would make the right side of your face sag. So during the surgery, electrodes will be inserted in your cheek, and your cheek will be repeatedly stimulated with tiny electrical pulses. The cortical responses will be recorded and fed into a loudspeaker so that the surgeon can immediately hear changes in the activity if his scalpel starts to stray into the area."

As Professor P. was driving home from his pre-surgery tests, his mind wandered from his current plight to his day at the hospital. "Quite interesting," he thought to himself. There were biopsychologists everywhere, doing biopsychological things. In all three labs he had visited, there were people who had begun their training as biopsychologists.

Two weeks later, Professor P. was rolled into the preparation room. "Sorry to do this, Professor P., you were my favorite instructor," the nurse said, as she inserted a large needle into Professor P.'s face and left it there.

Professor P. didn't mind; he was barely conscious. He did not know that he wouldn't regain consciousness for several days—at which point he would be incapable of talking, eating, or even breathing. But more about that later.

Don't forget Professor P.; you will learn more about him in Chapter 10. For the time being, this case demonstrates that many of the fundamental research methods of biopsychology are also used in clinical settings. Let's move on to the methods themselves.

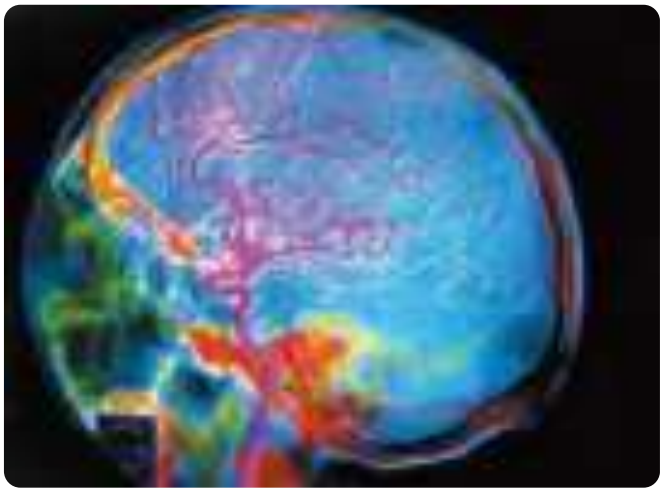
PART ONE Methods of Studying the Nervous System

This is the first of the two parts that compose this chapter. In this part, we present the methods used by biopsychologists to study the nervous system. As you will soon see, the methods are extremely diverse.

Methods of Visualizing and Stimulating the Living Human Brain

This module first describes four different sorts of methods for visualizing the living human brain: x-ray-based techniques, a radioactivity-based technique, magnetic-field-based techniques, and an ultrasound-based technique. Next, it presents three techniques for noninvasively stimulating the living human brain.

Figure 5.1 A cerebral angiogram of a healthy human.



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X-Ray-Based Techniques

LO 5.1 Describe two x-ray-based techniques for visualizing the living human brain.

Prior to the early 1970s, biopsychological research was impeded by the inability to obtain images of the organ of primary interest: the living human brain. Conventional x-ray photography is useless for this purpose. When an x-ray photograph is taken, an x-ray beam is passed through an object and then onto a photographic plate. Each molecule the beam has passed through absorbs some of the radiation; thus, only the unabsorbed portions of the beam reach the photographic plate. This makes x-ray photography effective in characterizing internal structures that absorb x-rays differently than their surroundings—just like a revolver in a suitcase full of clothes or a bone surrounded by flesh. However, by the time an x-ray beam has passed through the numerous overlapping structures of the brain, which differ only slightly in their ability to absorb x-rays, it carries little information about the structures through which it has passed.

CONTRAST X-RAYS. Although conventional x-ray photography is not useful for visualizing the brain, contrast x-ray techniques are. **Contrast x-ray techniques** involve injecting into one compartment of the body a substance that absorbs x-rays either less than or more than the surrounding tissue. The injected substance then heightens the contrast between the compartment and the surrounding tissue during x-ray photography.

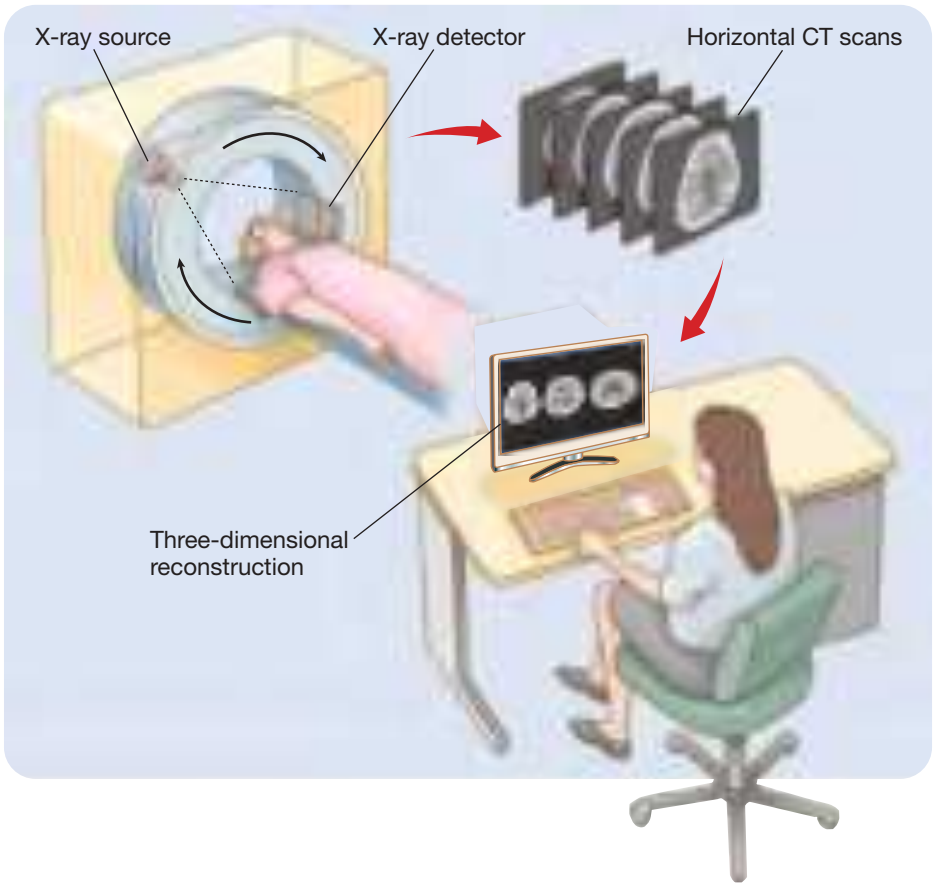
One contrast x-ray technique, **cerebral angiography**, uses the infusion of a radio-opaque dye into a cerebral artery to visualize the cerebral circulatory system during x-ray photography (see Figure 5.1). Cerebral angiograms are most useful for localizing vascular damage, but the displacement of blood vessels from their normal position also can indicate the location of a tumor.

Journal Prompt 5.1

Egas Moniz, the inventor of the lobotomy, was also the pioneer of cerebral angiography. Some have argued that Moniz's Nobel Prize for the lobotomy should have been revoked. However, others have argued that he would have won it anyway for his important work on cerebral angiography. Do you think Moniz deserved to win the Nobel Prize? Why or why not?

COMPUTED TOMOGRAPHY. In the early 1970s, the introduction of computed tomography revolutionized the study of the living human brain. **Computed tomography (CT)** is a computer-assisted x-ray procedure that can be used to visualize the brain and other internal structures of the living body. During cerebral computed tomography, the neurological patient lies with his or her head positioned in the center of a large cylinder, as depicted in Figure 5.2.

Figure 5.2 Computed tomography (CT) uses x-rays to create a brain scan.



On one side of the cylinder is an x-ray tube that projects an x-ray beam through the head to an x-ray detector mounted on the other side. The x-ray tube and detector rotate rapidly around the head of the patient at one level of the brain, taking many individual x-ray photographs as they rotate. The meager information in each x-ray photograph is combined by a computer to generate a CT scan of one horizontal section of the brain. Then the x-ray tube and detector are moved along the axis of the patient's body to another level of the brain, and the process is repeated. Scans of eight or nine horizontal brain sections are typically obtained from a patient. When combined, these images provide three-dimensional representations of the brain.

Radioactivity-Based Techniques

LO 5.2 Describe the positron emission tomography (PET) technique.

Positron emission tomography (PET) was the first brain-imaging technique to provide images of brain activity (*functional brain images*) rather than images of brain structure (*structural brain images*). In one common version of PET, radioactive **fluorodeoxyglucose (FDG)** is injected into the patient's *carotid artery* (an artery of the neck that feeds the ipsilateral cerebral hemisphere). Because of its similarity to glucose, the primary metabolic fuel of the brain, fluorodeoxyglucose is rapidly taken up by active (energy-consuming) cells. However, unlike glucose, fluorodeoxyglucose cannot be metabolized; it therefore accumulates in active neurons and astrocytes until it is gradually broken down (see Zimmer et al., 2017). Each PET scan is an image of the levels of radioactivity (indicated by color coding) in various parts of one horizontal level of the brain. Thus, if a PET scan is taken of a patient who engages in an activity such as reading for about 30 seconds after the FDG injection, the resulting scan will indicate the areas of the target brain level that were most active during the 30 seconds (see Figure 5.3).

Notice from Figure 5.3 that PET scans are not really images of the brain. Each PET scan is merely a colored map of the amount of radioactivity in each of the tiny cubic voxels (volume pixels) that compose the scan. Exactly how each voxel maps onto a particular brain structure can be estimated only by superimposing the scan on a brain image.

The most significant current application of PET technology is its use in identifying the distribution of particular molecules (e.g., neurotransmitters, receptors, transporters) in the brain (see Camardese et al., 2014). This is accomplished by injecting volunteers with radioactively labeled **ligands** (ions or molecules that bind to other molecules). Then, PET scans can document the distribution of radioactivity in the brain.

Magnetic-Field-Based Techniques

LO 5.3 Describe three magnetic-field-based techniques for imaging the living human brain.

MAGNETIC RESONANCE IMAGING. Magnetic resonance imaging (MRI) is a structural brain-imaging procedure in which high-resolution images are constructed from the measurement of radio-frequency waves that hydrogen atoms emit as they align with a powerful magnetic field. Such imaging is possible because: (1) water contains two hydrogen atoms (H_2O) and (2) different brain structures contain different amounts of water. This, in turn, means that the number of hydrogen atoms differs between brain structures, and, therefore, the radio-frequency waves emitted by a particular brain structure will be different from its neighboring brain structures. MRI provides clearer images of the brain than does CT (see Lerch et al., 2017). A two-dimensional MRI scan of the midsagittal plane of the brain is presented in Figure 5.4.

In addition to providing relatively high **spatial resolution** (the ability to detect and represent differences in spatial location), MRI can produce images in three

Figure 5.3 A pair of PET scans. A scan was done when the volunteer's eyes were either open (left) or closed (right). Areas of high activity are indicated by reds and yellows. Notice the high level of activity in the visual cortex of the occipital lobe when the volunteer's eyes were open.

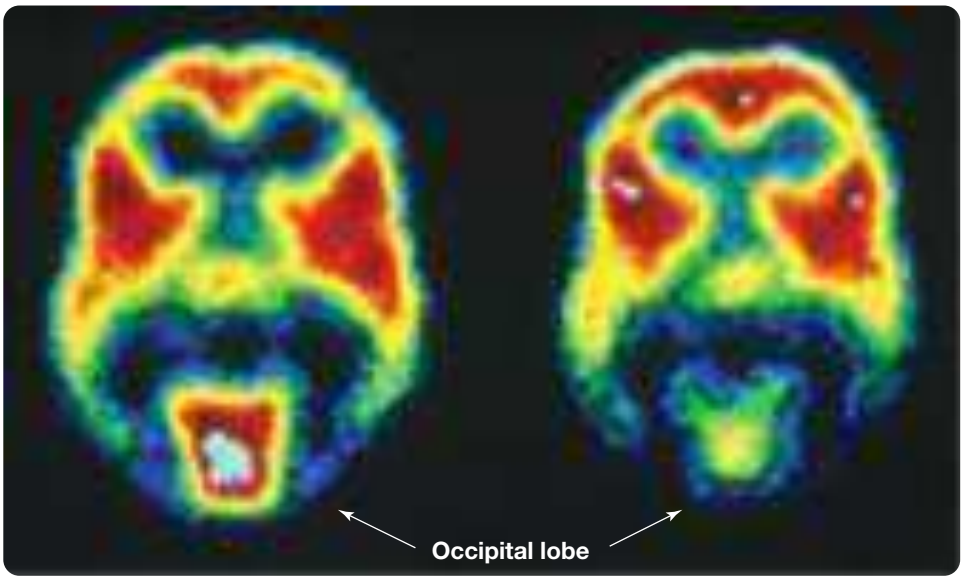


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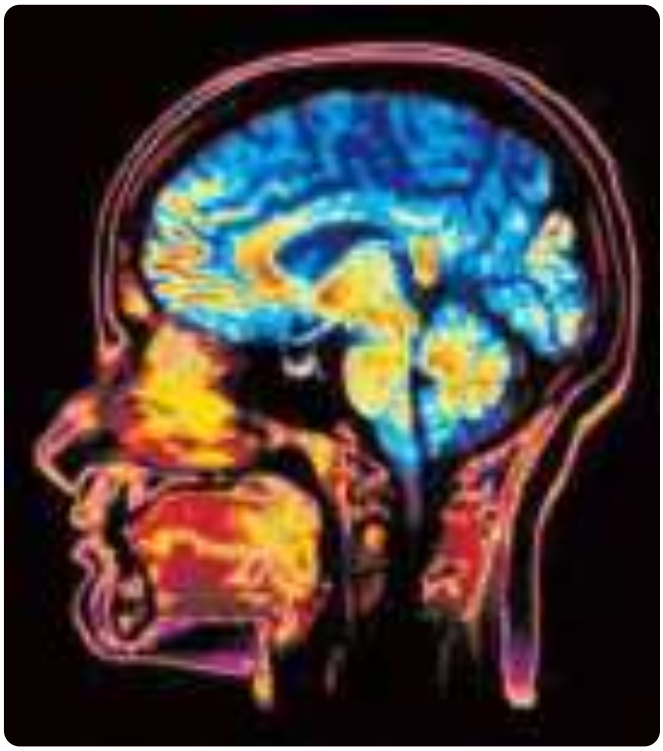
Figure 5.4 A color-enhanced midsagittal MRI scan.



Scott Camazine/Science Source

dimensions. Figure 5.5 shows a three-dimensional MRI scan of a patient with a growing tumor.

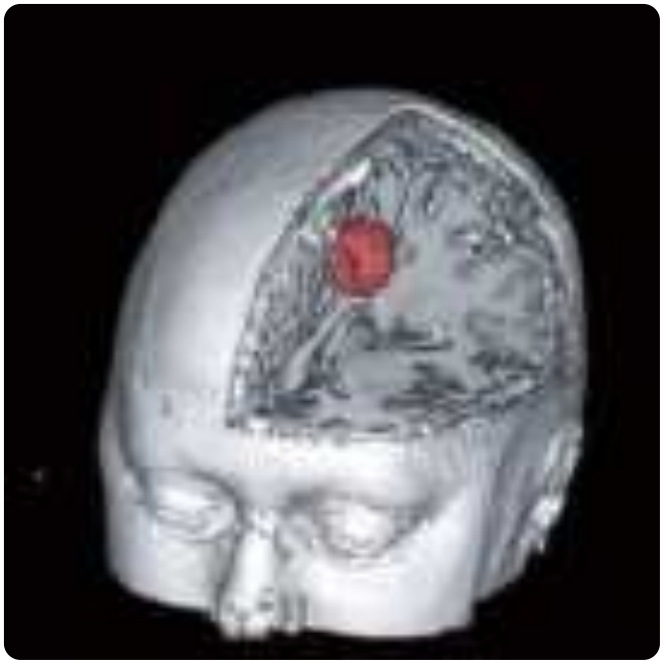
DIFFUSION TENSOR MRI. Many variations of MRI have been developed. Arguably, one of the most innovative of these new MRI techniques has been diffusion tensor MRI. **Diffusion tensor MRI** is a method of identifying those pathways along which water molecules rapidly diffuse (see Jbadi et al., 2015). Because *tracts* (bundles of axons) are the major routes of rapid water diffusion in the brain, diffusion tensor imaging provides an image of major tracts—see Figure 5.6.

Most brain research focuses on the structures of the brain. However, in order to understand how the brain works, it is imperative to understand the connections among those structures—the so-called *connectome* (see Park & Friston, 2013; Glasser et al., 2016; Swanson & Lichtman, 2016). This is why diffusion tensor images have become a focus of neuroscientific research. Complete descriptions of connectomes already exist for some organisms, including the nematode *C. elegans* and the mouse (see Oh et al., 2014). Work on the so-called *Human Connectome Project* is well underway.

FUNCTIONAL MRI. MRI technology has been used to produce functional images of the brain. Indeed, functional MRI has become the most influential tool of cognitive neuroscience. It is often used to determine if a brain is dysfunctional, but it is also used for a variety of other purposes; for example, to infer the content of an individual's dreams (see Horikawa et al., 2013; Underwood, 2013).

Functional MRI (fMRI) produces images representing the increase in oxygenated blood flow to active areas of the brain. Functional MRI is possible because of two attributes of oxygenated blood. First, active areas of the brain take up more oxygenated blood than they need for their energy requirements, and thus oxygenated blood accumulates in active areas of the brain (see

Figure 5.5 MRI of a growing tumor. The tumor is colored red.



Simon Fraser/Science Source

Figure 5.6 Diffusion tensor MRI. This three-dimensional image shows the major tracts of the brain.

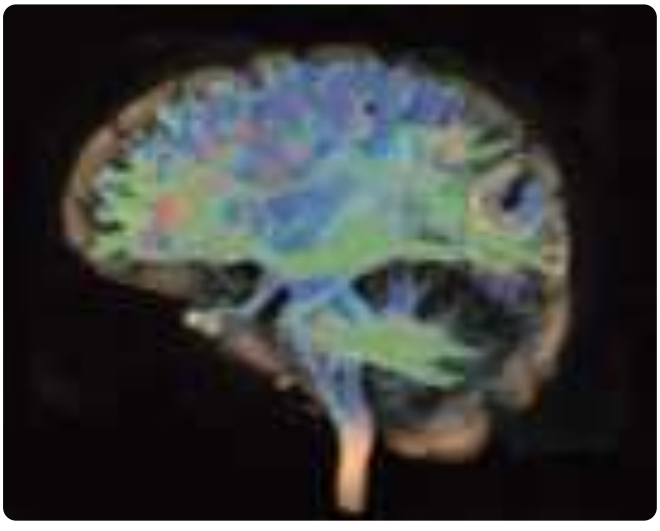


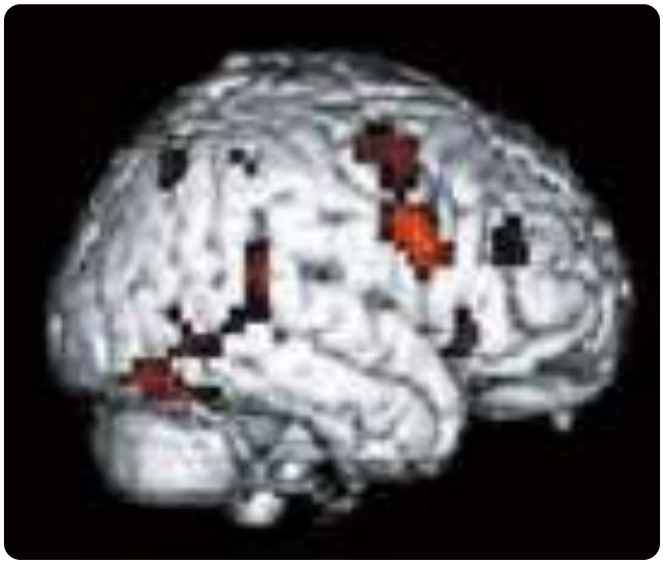
Image Source/Alamy Stock Photo

Hillman, 2014). Second, oxygenated blood has different magnetic properties than does deoxygenated blood, and this difference influences the radio-frequency waves emitted by hydrogen atoms in an MRI. The signal recorded by fMRI is called the **BOLD signal** (the blood-oxygen-level-dependent signal). The BOLD signal indicates the parts of the brain that are active or inactive during a cognitive or behavioral test, and thus it suggests the types of analyses the brain is performing. Because the BOLD signal is the result of blood flow through the brain, it is important to remember that it is not directly measuring the electrical activity of the brain.

Functional MRI has three advantages over PET: (1) nothing has to be injected into the volunteer; (2) it provides both structural and functional information in the same image; and (3) its spatial resolution is better. A functional MRI is shown in Figure 5.7.

It is important not to be unduly swayed by the impressiveness of fMRI images and technology. The images are often presented—particularly in the popular press or general textbooks—as if they are actual pictures of human neural activity. They aren't: They are images of the BOLD signal, and the relation between the BOLD signal and neural activity is complex (see Hillman, 2014). Furthermore, fMRI technology has poor **temporal resolution**, that is, it is poor at specifying the timing of neural events. Indeed, it takes 2 or 3 seconds to measure the BOLD signal, and many neural responses, such as action potentials, occur in the millisecond range.

Figure 5.7 Functional magnetic resonance image (fMRI). This image illustrates the areas of cortex that became more active when the volunteers observed strings of letters and were required to specify which strings were words—in the control condition, volunteers viewed strings of asterisks (Kiehl et al., 1999). This fMRI illustrates surface activity; but images of sections through the brain can also be displayed.



Kent Kiehl/Peter Liddle/University of British Columbia Department of Psychiatry

Ultrasound-Based Techniques

LO 5.4 Describe an ultrasound-based technique for imaging the living human brain.

Functional ultrasound imaging (fUS) is a new imaging technique that uses *ultrasound* (sound waves of a higher frequency than we can hear) to measure changes in blood volume in particular brain regions. When a brain region becomes active, blood levels increase there, and alter the passage of ultrasound through that brain region.

As a functional brain imaging method, fUS has three key advantages over PET and fMRI: (1) it is cheap, (2) highly portable; and (3) can be used for imaging some individuals, such as human infants, who cannot undergo PET or fMRI (see Deffieux et al., 2018).

Transcranial Stimulation

LO 5.5 Describe three transcranial stimulation techniques.

PET, fMRI, and fUS have allowed cognitive neuroscientists to create images of brain activity while volunteers are engaging in particular cognitive activities. Although technically impressive, these kinds of studies of brain activity and cognition all have the same shortcoming: They can be used to show a *correlation* between brain activity and cognitive activity, but they can't prove that the brain activity *caused* the cognitive activity (Sack, 2006). For example, a brain-imaging technique may show that the cingulate cortex becomes active when volunteers view disturbing photographs, but it can't prove that the cingulate activity causes the emotional experience—there are many other explanations. There are two obvious ways of supporting the hypothesis that the cingulate cortex is an area for emotional experience. One way would be to assess emotional experience in people lacking a functional cingulate cortex. This can be accomplished by studying patients with cingulate damage or by "turning off" the cingulate cortex of healthy patients—transcranial magnetic stimulation is a way of turning off particular areas of cortex. A second way would be to assess emotional experiences of volunteers after "turning on" their cingulate cortex—transcranial electrical stimulation and transcranial ultrasound stimulation are ways of turning on areas of cortex.

Let us briefly introduce you to transcranial magnetic stimulation and transcranial electrical stimulation, which are currently playing a major role in establishing the causal effects of human cortical activity on cognition and behavior. **Transcranial magnetic stimulation (TMS)** is a

technique that can be used to turn off an area of human cortex by creating a magnetic field under a coil positioned next to the skull (e.g., Candidi et al., 2015). The magnetic stimulation temporarily turns off part of the brain while the effects of the disruption on cognition and behavior are assessed. Although there are still fundamental questions about safety, depth of effect, and mechanisms of neural disruption (see Polanía, Nitsche, & Ruff, 2018; Romei, Thut, & Silvanto, 2016), TMS is often employed to circumvent the difficulty that brain-imaging studies have in determining causation. Using different stimulation parameters, TMS can also be used to "turn on" an area of cortex (see Rossini et al., 2015).

Transcranial electrical stimulation (tES) is a technique that can be used to stimulate ("turn on") an area of the cortex by applying an electrical current through two electrodes placed directly on the scalp. The electrical stimulation temporarily increases activity in part of the brain while the effects of the stimulation on cognition and behavior are assessed (see Polanía, Nitsche, & Ruff, 2018).

The use of tES for its putative cognitive enhancement effects has become popular, and there are many relatively inexpensive tES systems available for purchase online (see Bourzac, 2016). However, there is conflicting evidence about whether tES has beneficial effects on cognition; some studies have even reported detrimental effects. Differing stimulation protocols might account for some of the discrepant findings (see Sellers et al., 2015).

Transcranial ultrasound stimulation (tUS) is a technique that, like tES and TMS, can be used to activate particular brain structures. However, unlike tES and TMS, which can only be used to stimulate cortical structures, tUS can also be used to activate subcortical structures.

To activate a brain structure using tUS, multiple sources of low-amplitude ultrasonic sound waves are placed around the head of the individual. Then, each of those sound sources is directed at the target brain structure. When the ultrasonic sound waves from each of those sources reach the target structure they sum together, such that the amplitude of the sound waves at the target brain structure is sufficiently large to stimulate activity in the cells there (see Tyler, Lani, & Hwang, 2018).

The tUS technique can also be used to make small permanent lesions to a brain structure. The procedure is the same as that for stimulation via tUS, except that the amplitude of each ultrasound source is larger, leading to a larger amplitude waveform that is sufficient to create a small (e.g., the size of a grain of rice) permanent lesion. This tUS-based lesion method has been used to treat several conditions (e.g., lesioning a thalamic nucleus to treat essential tremor)—all without having to make an incision. Accordingly, the tUS lesion technique is revolutionizing neurosurgery (see Landhuis, 2017).

Recording Human Psychophysiological Activity

The preceding module introduced you to structural and functional brain imaging. This module deals with *psychophysiological recording methods* (methods of recording physiological activity from the surface of the human body). Six of the most widely studied psychophysiological measures are described: two measures of brain activity (the scalp EEG and magnetoencephalography), two measures of somatic nervous system activity (muscle tension and eye movement), and two measures of autonomic nervous system activity (skin conductance and cardiovascular activity).

Psychophysiological Measures of Brain Activity

LO 5.6 Describe two psychophysiological measures of brain activity.

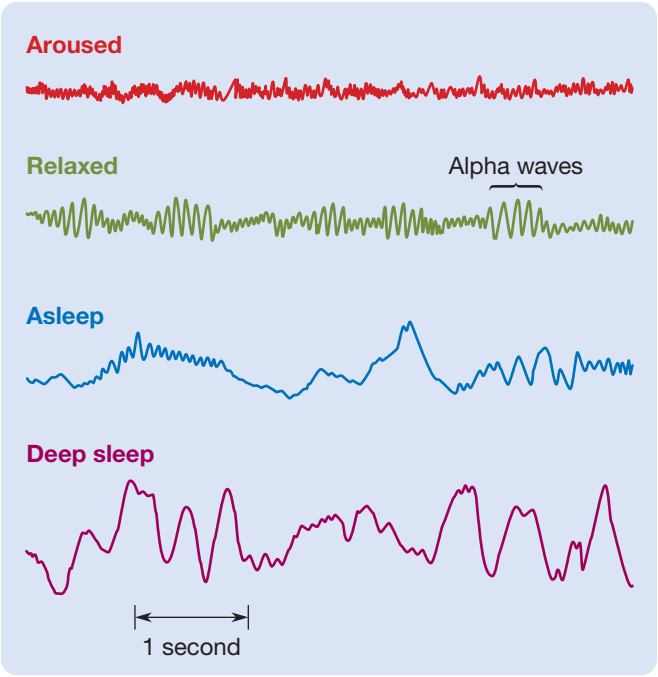
SCALP ELECTROENCEPHALOGRAPHY. The *electroencephalogram* (*EEG*) is a measure of the gross electrical activity of the brain. It is recorded through large electrodes by a device called an *electroencephalograph* (*EEG machine*), and the technique is called **electroencephalography**. In EEG studies of human participants, each channel of EEG activity is usually recorded from disk-shaped electrodes, about half the size of a dime, which are attached to the scalp.

The scalp EEG signal reflects the sum of electrical events throughout the head. These events include action potentials and postsynaptic potentials as well as electrical signals from the skin, muscles, blood, and eyes.

Thus, the utility of the scalp EEG does not lie in its ability to provide an unclouded view of neural activity. Its value as a research and diagnostic tool rests on the fact that some EEG wave forms are associated with particular states of consciousness or particular types of cerebral pathology (e.g., epilepsy). For example, **alpha waves** are regular, 8- to 12-per-second, high-amplitude waves that are associated with relaxed wakefulness. A few examples of EEG wave forms and their psychological correlates are presented in Figure 5.8.

Because EEG signals decrease in amplitude as they spread from their source, a comparison of signals recorded from various sites on the scalp can sometimes indicate the origin of particular waves (see Cohen, 2017). This is why it is usual to record EEG activity from many sites simultaneously.

Figure 5.8 Some typical electroencephalograms and their psychological correlates.



Psychophysiologists are often more interested in the EEG waves that accompany certain psychological events than in the background EEG signal. These accompanying EEG waves are generally referred to as **event-related potentials (ERPs)**. One commonly studied type of event-related potential is the **sensory evoked potential**—the change in the cortical EEG signal elicited by the momentary presentation of a sensory stimulus. As Figure 5.9 illustrates, the cortical EEG that follows a sensory stimulus has two components: the response to the stimulus (the signal) and the ongoing background EEG activity (the noise). The *signal* is the part of any recording that is of interest; the *noise* is the part that isn't. The problem in recording sensory evoked potentials is that the noise of the background EEG is often so great that the sensory evoked potential is masked. Measuring a sensory evoked potential can be like detecting a whisper at a rock concert.

A method used to reduce the noise of the background EEG is **signal averaging**. First, a subject's response to a stimulus, such as a click, is recorded many—let's say 1,000—times. Then, a computer identifies the millivolt value of each of the 1,000 traces at its starting point (i.e., at the click) and calculates the mean of these 1,000 scores. Next, it considers the value of each of the 1,000 traces 1 millisecond (msec) from its start, for example, and calculates the mean of these values. It repeats this process at the 2-msec mark, the 3-msec mark, and so on. When these averages are plotted, the average response evoked by the click is more apparent because the random background EEG is canceled out by the averaging. See Figure 5.9, which illustrates the averaging of an auditory evoked potential.

The analysis of *average evoked potentials* (*AEPs*) focuses on the various waves in the averaged signal. Each wave is characterized by its direction, positive or negative, and by its latency. For example, the **P300 wave** illustrated in Figure 5.10 is the positive wave that occurs about 300 milliseconds after a momentary stimulus that has meaning for the participant (e.g., a stimulus to which the

Figure 5.9 Signal averaging: Averaging of the background EEG (left) and of auditory evoked potentials (right). Averaging increases the signal-to-noise ratio.

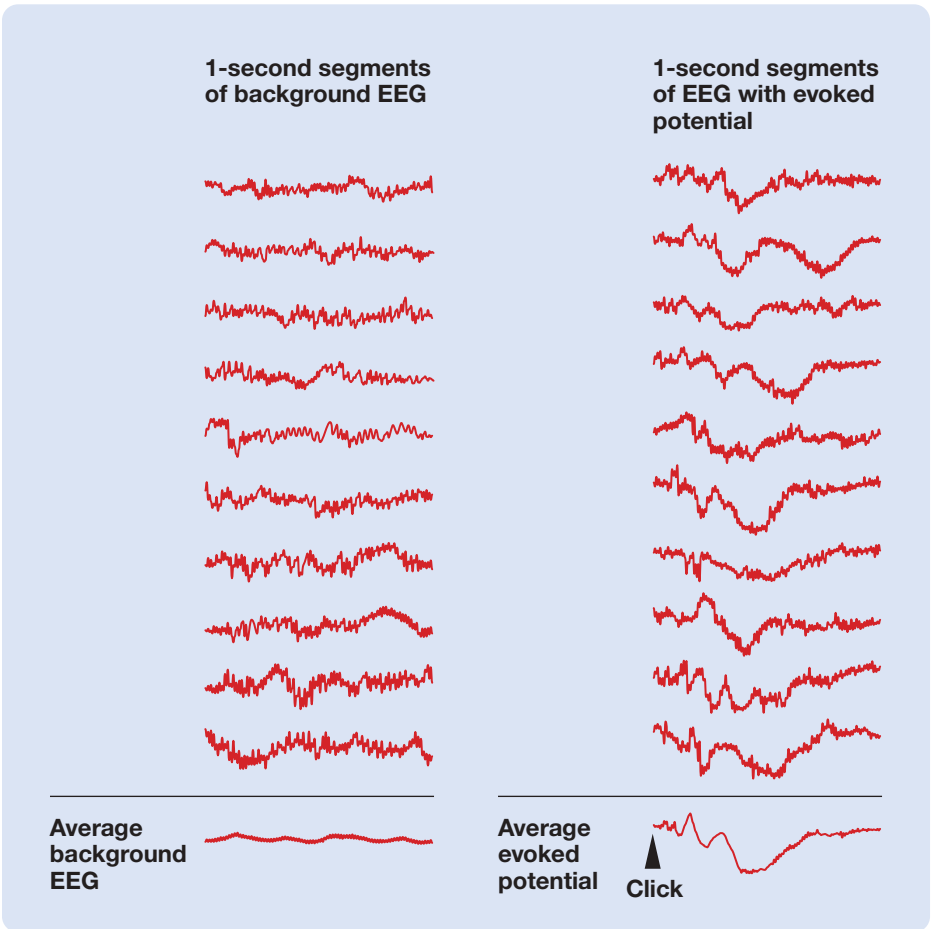


Figure 5.10 An average auditory evoked potential. Notice the P300 wave. This wave occurs only if the stimulus has meaning for the participant; in this case, the 'click' sound signals the imminent delivery of a reward. By convention, positive EEG waves are always shown as downward deflections.

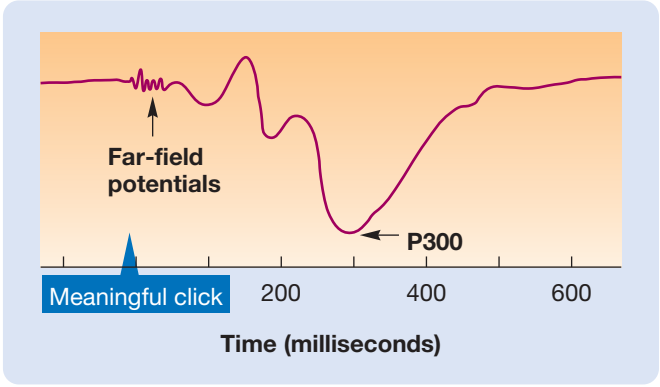


Figure 5.11 A magnetoencephalography (MEG) machine. Stylish in any home!

Image Source/Alamy Stock Photo

participant must respond). In contrast, the portions of an evoked potential recorded in the first few milliseconds after a stimulus are not influenced by the meaning of the stimulus for the participant. These small waves are called **far-field potentials** because, although they are recorded from the scalp, they originate far away in the sensory nuclei of the brain stem.

MAGNETOENCEPHALOGRAPHY. Another technique used to monitor brain activity from the scalp of human subjects is **magnetoencephalography (MEG)**. MEG measures changes in magnetic fields on the surface of the scalp that are produced by changes in underlying patterns of neural activity. Because the magnetic signals induced by neural activity are so small, only those induced near the surface of the brain can be recorded from the scalp (see Hari & Parkkonen, 2015).

MEG has two major advantages over EEG. First, it has much better spatial resolution than EEG; that is, it can localize changes in electrical activity in the cortex with greater precision. Second, MEG can be used to localize subcortical activity with greater reliability than EEG (Baillet, 2017). Some downsides to the use of MEG include its high price, the large size of the MEG machines (see Figure 5.11), and the requirement that participants remain very still during recordings (Baillet, 2017; but see Boto et al., 2018).

Psychophysiological Measures of Somatic Nervous System Activity

LO 5.7 **Describe two psychophysiological measures of somatic nervous system activity.**

MUSCLE TENSION. Each skeletal muscle is composed of millions of threadlike muscle fibers. Each muscle fiber contracts in an all-or-none fashion when activated by the motor neuron that innervates it. At any given time, a few fibers in each resting muscle are likely to be contracting, thus maintaining the overall tone (tension) of the muscle. Movement results when a large number of fibers contract at the same time.

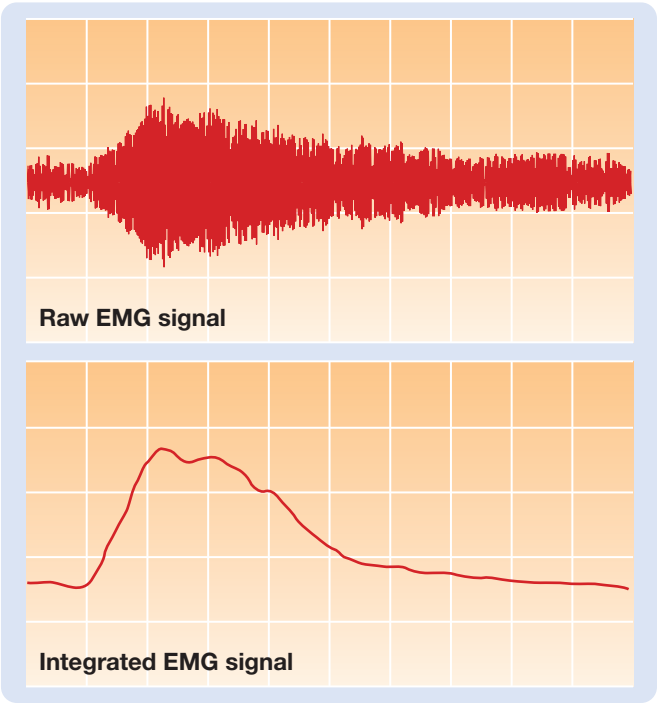
In everyday language, anxious people are commonly referred to as "tense." This usage acknowledges the fact that anxious or otherwise aroused individuals typically display high resting levels of tension in their muscles. This is why psychophysiologists are interested in this measure; they use it as an indicator of psychological arousal.

Electromyography is the usual procedure for measuring muscle tension. The resulting record is called an *electromyogram* (*EMG*). EMG activity is usually recorded between two electrodes taped to the surface of the skin over the muscle of interest. An EMG record is presented in Figure 5.12. You will notice from this figure that the main correlate of an increase in muscle contraction is an increase in the amplitude of the raw EMG signal, which reflects the number of muscle fibers contracting at any one time.

Most psychophysiologists do not work with raw EMG signals; they convert them to a more workable form. The raw signal is fed into a computer that calculates the total amount of EMG spiking per unit of time—in consecutive 0.1-second intervals, for example. The integrated signal (i.e., the total EMG activity per unit of time) is then plotted. The result is a smooth curve, the amplitude of which is a simple, continuous measure of the level of muscle tension (see Figure 5.12).

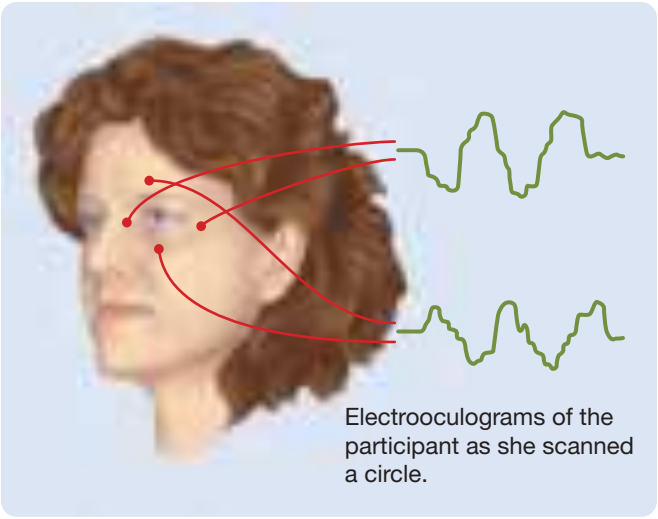
EYE MOVEMENT. The electrophysiological technique for recording eye movements is called **electrooculography**, and the resulting record is called an *electrooculogram* (*EOG*). Electrooculography is based on the fact that a steady potential difference exists between the front (positive) and

Figure 5.12 The relation between a raw EMG signal and its integrated version. The volunteer tensed her muscle beneath the electrodes and then gradually relaxed it.



back (negative) of the eyeball. Because of this steady potential, when the eye moves, a change in the electrical potential between electrodes placed around the eye can be recorded. It is usual to record EOG activity between two electrodes placed on each side of the eye to measure its horizontal movements and between two electrodes placed above and below the eye to measure its vertical movements (see Figure 5.13).

Figure 5.13 The typical placement of electrodes around the eye for electrooculography. The two electrooculogram traces were recorded as the volunteer scanned a circle.



Psychophysiological Measures of Autonomic Nervous System Activity

LO 5.8 **Describe two psychophysiological measures of autonomic nervous system activity.**

SKIN CONDUCTANCE. Emotional thoughts and experiences are associated with increases in the ability of the skin to conduct electricity. The two most commonly employed indexes of *electrodermal activity* are the **skin conductance level (SCL)** and the **skin conductance response (SCR)**. The SCL is a measure of the background level of skin conductance that is associated with a particular situation, whereas the SCR is a measure of the transient changes in skin conductance that are associated with discrete experiences.

The physiological bases of skin conductance changes are not fully understood, but there is considerable evidence implicating the sweat glands. Although the main function of sweat glands is to cool the body, these glands tend to become active in emotional situations, causing the release of sweat that in turn increases the electrical conductivity of the skin (see Green et al., 2014). Sweat glands are distributed over most of the body surface, but, as you are almost certainly aware, those of the hands, feet, armpits, and forehead are particularly responsive to emotional stimuli.

CARDIOVASCULAR ACTIVITY. The presence in our language of phrases such as *white with fear* and *blushing bride* indicates that modern psychophysiologists were not the first to recognize the relationship between *cardiovascular activity* and emotion. The cardiovascular system has two parts: the blood vessels and the heart. It is a system for distributing oxygen and nutrients to the tissues of the body, removing metabolic wastes, and transmitting chemical messages. Three different measures of cardiovascular activity are frequently employed in psychophysiological research: heart rate, arterial blood pressure, and local blood volume.

Heart Rate The electrical signal associated with each heartbeat can be recorded through electrodes placed on the chest. The recording is called an **electrocardiogram** (abbreviated either **ECG**, for obvious reasons, or **EKG**, from the original German). The average resting heart rate of a healthy adult is about 70 beats per minute, but it increases abruptly at the sound, or thought, of a dental drill.

Blood Pressure Measuring arterial blood pressure involves two independent measurements: a measurement of the peak pressure during the periods of heart contraction, the *systoles*, and a measurement of the minimum pressure during the periods of relaxation, the *diastoles*. Blood pressure is usually expressed as a ratio of systolic over diastolic

blood pressure in millimeters of mercury (mmHg). The normal resting blood pressure for an adult is about 130/70 mmHg. A chronic blood pressure of more than 140/90 mmHg is viewed as a serious health hazard and is called **hypertension**.

You have likely had your blood pressure measured with a *sphygmomanometer*—a crude device composed of a hollow cuff, a rubber bulb for inflating it, and a pressure gauge for measuring the pressure in the cuff (*sphygmos* means "pulse"). More reliable, fully automated methods are used in research.

Blood Volume Changes in the volume of blood in particular parts of the body are associated with psychological events. The best-known example of such a change is the engorgement of the genitals associated with sexual arousal in both males and females. **Plethysmography** refers to the various techniques for measuring changes in the volume of blood in a particular part of the body (*plethysmos* means "an enlargement").

One method of measuring these changes is to record the volume of the target tissue by wrapping a strain gauge around it. Although this method has utility in measuring blood flow in fingers or similarly shaped organs, the possibilities for employing it are somewhat limited. Another plethysmographic method is to shine a light through the tissue under investigation and to measure the amount of light absorbed by it. The more blood there is in a structure, the more light it will absorb.

Invasive Physiological Research Methods

We turn now from a consideration of the noninvasive techniques employed in research on living human brains to a consideration of more direct techniques, which are commonly employed in biopsychological studies of nonhuman animals. Most physiological techniques used in biopsychological research on nonhuman animals fall into one of three categories: lesion methods, electrical stimulation methods, and invasive recording methods. Each of these three methods is discussed in this module, but we begin with a description of *stereotaxic surgery* because each of these methods involves the use of stereotaxic surgery.

Stereotaxic Surgery

LO 5.9 Describe the process of stereotaxic surgery.

Stereotaxic surgery is the first step in many biopsychological experiments. *Stereotaxic surgery* is the means by which experimental devices are precisely positioned in the depths of the brain. Two things are required in stereotaxic surgery: an atlas to provide directions to the target site and an instrument for getting there.

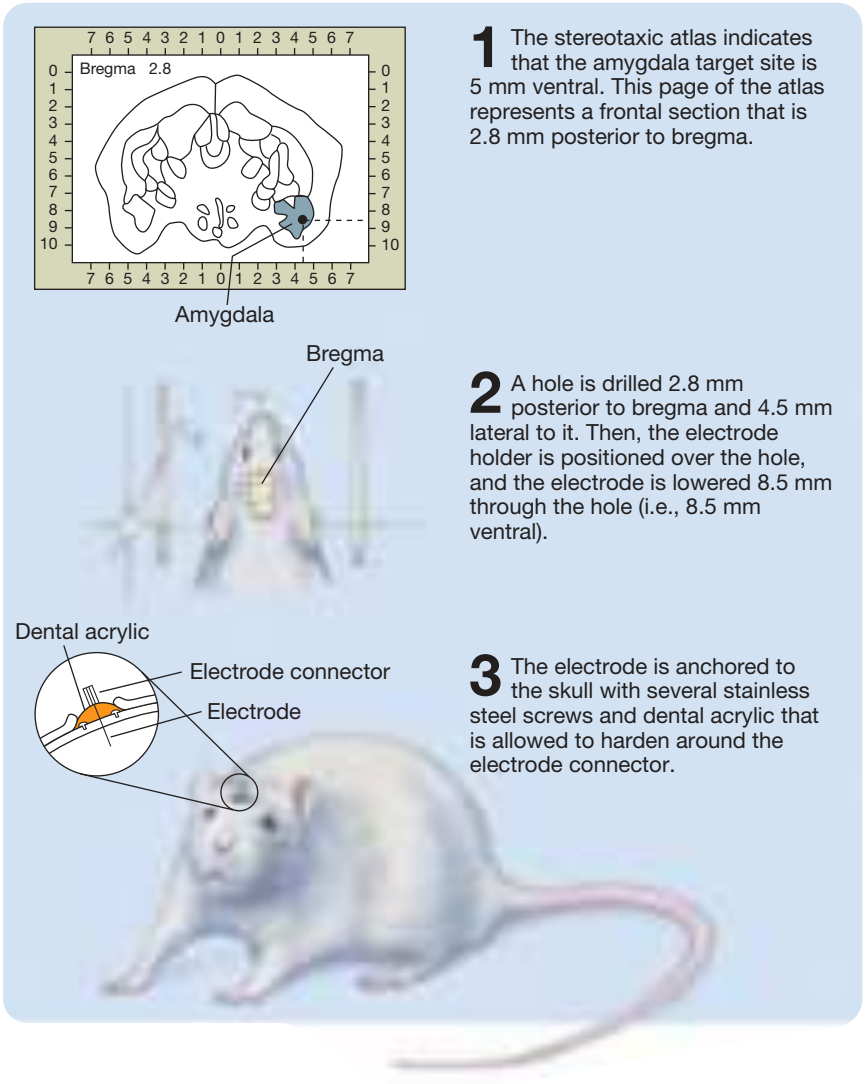
The **stereotaxic atlas** is used to locate brain structures in much the same way that a geographic atlas is used to locate geographic landmarks. There is, however, one important difference. In contrast to the surface of the earth, which has only two dimensions, the brain has three. Accordingly, the brain is represented in a stereotaxic atlas by a series of individual maps, one per page, each representing the structure of a single, two-dimensional frontal brain slice. In stereotaxic atlases, all distances are given in millimeters from a designated reference point. In most rat atlases, the reference point is **bregma**—the point on the top of the skull where two of the major *sutures* (seams in the skull) intersect.

The **stereotaxic instrument** (see Figure 5.14) has two parts: a *head holder*, which firmly holds each subject's brain in the prescribed position and orientation; and an *electrode holder*, which holds the device to be inserted. A system of precision gears allows the electrode holder to be moved in three dimensions: anterior–posterior, dorsal–ventral, and lateral–medial. The implantation by stereotaxic surgery of an electrode in the amygdala of a rat is illustrated in Figure 5.15.

Figure 5.14 A stereotaxic instrument. This one is meant for surgery on rodents.

Model 900 Small Animal Stereotaxic Instrument originally designed by David Kopf Instruments in 1963.

Figure 5.15 Stereotaxic surgery: Implanting an electrode in the rat amygdala.



Lesion Methods

LO 5.10 Describe four types of lesion methods and explain why it is important to be cautious when interpreting the effects of lesions.

Those of you with an unrelenting drive to dismantle objects to see how they work will appreciate the lesion methods. In those methods, a part of the brain is damaged, destroyed, or inactivated; then the behavior of the subject is carefully assessed in an effort to determine the functions of the lesioned structure. Four types of lesions are discussed here: aspiration lesions, radio-frequency lesions, knife cuts, and reversible lesions.

ASPIRATION LESIONS. When a lesion is to be made in an area of cortical tissue that is accessible to the eyes and instruments of the surgeon, **aspiration** is frequently the method of choice. The cortical tissue is drawn off by suction through a fine-tipped handheld glass pipette. Because the underlying white matter is slightly more resistant to suction than the cortical tissue itself, a skilled surgeon can delicately peel off the layers of cortical tissue from the surface of the brain, leaving the underlying white matter and major blood vessels undamaged.

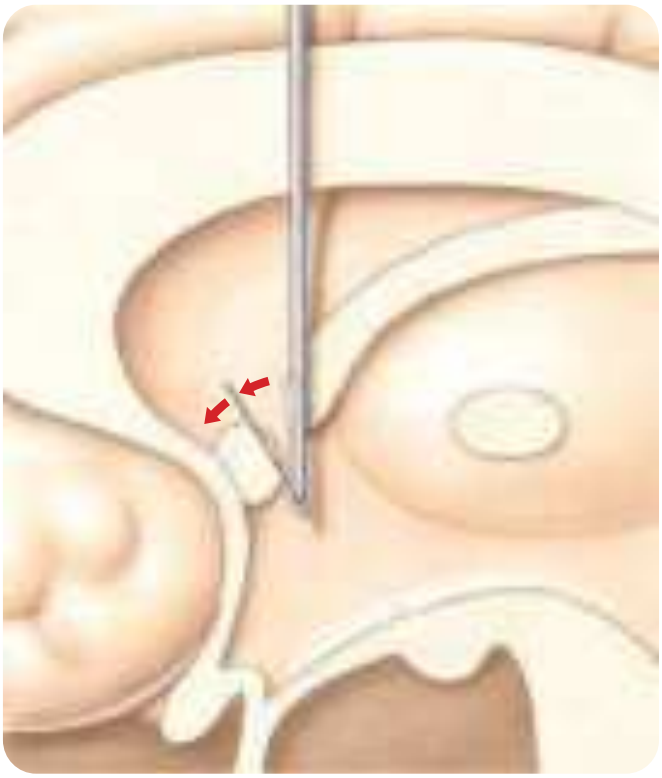
RADIO-FREQUENCY LESIONS. Small subcortical lesions are commonly made by passing *radio-frequency current* (high-frequency current) through the target tissue from the tip of a stereotaxically positioned electrode. The heat from the current destroys the tissue. The size and shape of the lesion are determined by the duration and intensity of the current and the configuration of the electrode tip.

KNIFE CUTS. *Sectioning* (cutting) is used to eliminate conduction in a nerve or tract. A tiny, well-placed cut can unambiguously accomplish this task without producing extensive damage to surrounding tissue. How does one insert a knife into the brain to make a cut without severely damaging the overlying tissue? One method is depicted in Figure 5.16.

REVERSIBLE LESIONS. Reversible lesions are useful alternatives to *destructive lesions*. **Reversible lesions** are methods for temporarily eliminating the activity in a particular area of the brain while tests are being conducted. The advantage of reversible lesions is that the same subjects can be repeatedly tested in both the lesion and control conditions. The two most common methods of producing a reversible lesion are by temporarily cooling the target structure or by injecting an anesthetic (e.g., *lidocaine*) into it.

INTERPRETING LESION EFFECTS. Before you leave this section on lesions, a word of caution is in order. Lesion effects are deceptively difficult to interpret. Because the structures of the brain are small, convoluted, and tightly packed together, even a highly skilled surgeon cannot completely destroy a structure without producing significant damage to adjacent structures. There is, however, an unfortunate tendency to lose sight of this fact. For example, a lesion that leaves major portions of the amygdala intact and damages an assortment of neighboring structures comes to be thought of simplistically as an *amygdala lesion*. Such an apparently harmless abstraction can be misleading in two ways. If you believe that all lesions referred to as "amygdala lesions" include damage to no other brain structure, you may incorrectly attribute all of their behavioral effects

Figure 5.16 A device for performing subcortical knife cuts. The device is stereotaxically positioned in the brain; then the blade swings out to make the cut. Here, the anterior commissure is being sectioned.



to amygdala damage; conversely, if you believe that all lesions referred to as "amygdala lesions" include the entire amygdala, you may incorrectly conclude that the amygdala does not participate in behaviors uninfluenced by the lesion.

BILATERAL AND UNILATERAL LESIONS. As a general principle—but one with several notable exceptions—the behavioral effects of *unilateral lesions* (lesions restricted to one half of the brain) are much milder than those of symmetrical *bilateral lesions* (lesions involving both sides of the brain), particularly in nonhuman species. Indeed, behavioral effects of unilateral lesions to some brain structures can be difficult to detect. As a result, most experimental studies of lesion effects are studies of bilateral, rather than unilateral, lesions.

Electrical Stimulation

LO 5.11 Describe the technique of electrical brain stimulation.

Clues about the function of a neural structure can be obtained by stimulating it electrically. Electrical brain stimulation is usually delivered across the two tips of a *bipolar electrode*—two insulated wires wound tightly together and cut at the end. Weak pulses of current produce an immediate increase in the firing of neurons near the tip of the electrode.

Electrical stimulation of the brain is an important biopsychological research tool because it often has behavioral effects, usually opposite to those produced by a lesion to the same site. It can elicit a number of behavioral sequences, including eating, drinking, attacking, copulating, and sleeping. The particular behavioral response elicited depends on the location of the electrode tip, the parameters of the current, and the test environment in which the stimulation is administered.

Because electrical stimulation of the brain is an invasive procedure, its use is usually limited to nonhumans. However, sometimes the brains of conscious human patients are stimulated for therapeutic reasons (e.g., Jonas et al., 2014).

Invasive Electrophysiological Recording Methods

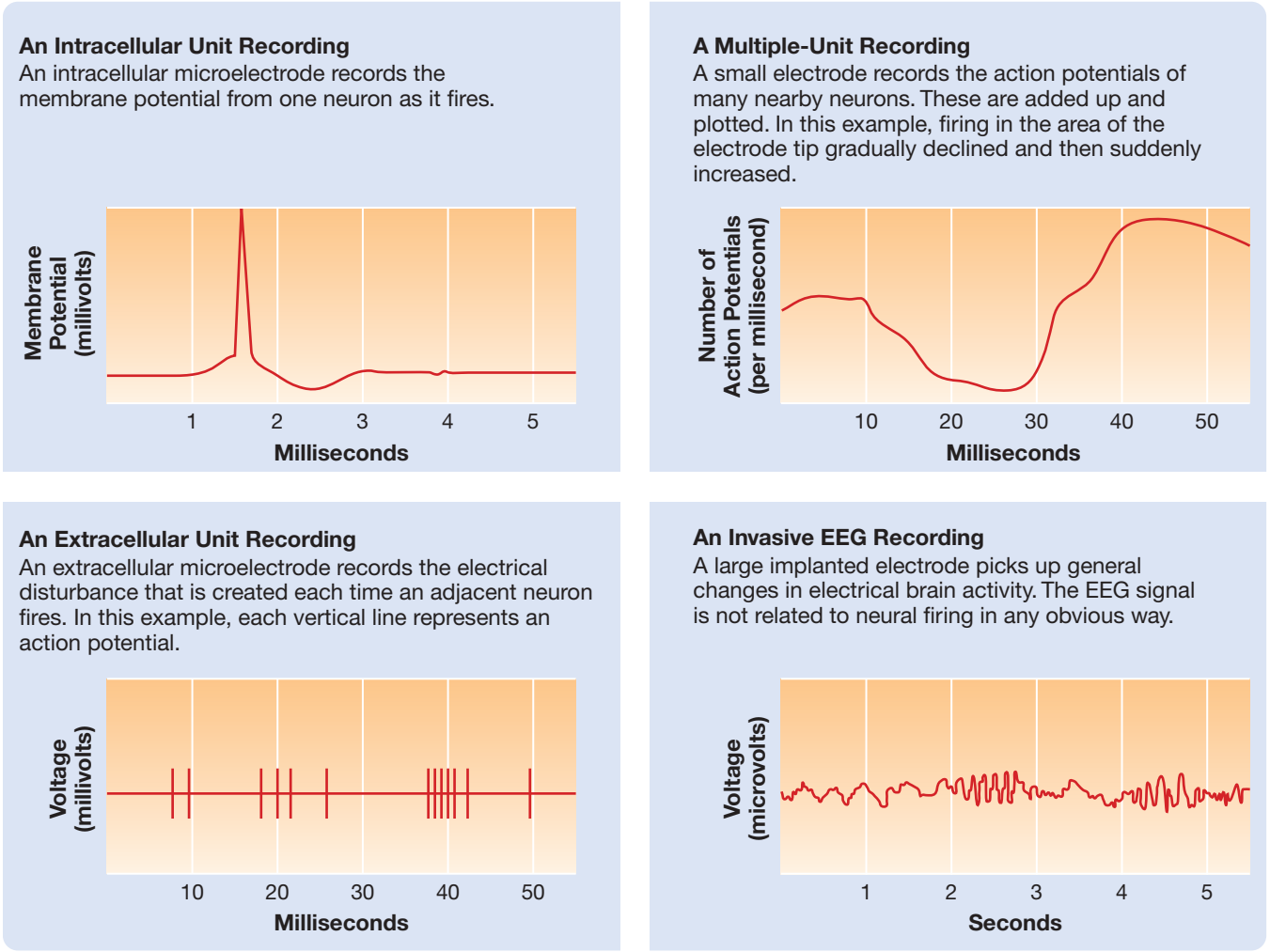
LO 5.12 Describe four invasive electrophysiological recording methods.

This section describes four invasive electrophysiological recording methods: intracellular unit recording, extracellular unit recording, multiple-unit recording, and invasive EEG recording. See Figure 5.17 for an example of each method.

INTRACELLULAR UNIT RECORDING. This method provides a moment-by-moment record of the graded fluctuations in one neuron's membrane potential. Most experiments using this recording procedure are performed on chemically immobilized animals because it is difficult to keep the tip of a microelectrode positioned inside a neuron of a freely moving animal (see Long & Lee, 2012). However, special electrodes are now being developed that can allow researchers to do intracellular recordings in a freely moving animal (see Lee & Brecht, 2018).

EXTRACELLULAR UNIT RECORDING. With extracellular unit recording, it is possible to record the activity of a neuron through a microelectrode whose tip is positioned in the extracellular fluid next to it—each time the neuron fires, there is an electrical disturbance and a blip is recorded at the electrode tip. Accordingly, *extracellular unit recording* provides a record of the firing of a neuron but no information about the neuron's membrane potential. It is difficult to record extracellularly from a single neuron in a freely moving animal without the electrode tip shifting away from that neuron, but it can be accomplished with special flexible microelectrodes that can shift slightly with the brain. Initially, extracellular unit recording involved recording from one neuron at a time, each at the tip of a separately implanted electrode. However, it is now possible to simultaneously record extracellular signals from up to about 1,000 neurons by analyzing the correlations among the signals picked up

Figure 5.17 Four methods of recording electrical activity of the nervous system.



through several different electrodes implanted in the same general area (see Callaway & Garg, 2017; Harris et al., 2016; Jun et al., 2017).

MULTIPLE-UNIT RECORDING. In *multiple-unit recording*, the electrode tip is much larger than that of a microelectrode; thus, it picks up signals from many neurons, and slight shifts in its position due to movement of the subject have little effect on the overall signal. The many action potentials picked up by the electrode are fed into an integrating circuit, which adds them together. A multiple-unit recording is a graph of the total number of recorded action potentials per unit of time (e.g., per 0.1 second).

INVASIVE EEG RECORDING. In nonhuman animals, and sometimes in human patients (see Fox et al., 2018), EEG signals can be recorded through implanted electrodes rather than through scalp electrodes. In nonhuman animals, cortical EEG signals are frequently recorded through stainless steel skull screws, whereas subcortical EEG signals are typically recorded through implanted wire electrodes.

Pharmacological Research Methods

In the preceding module, you learned how physiological psychologists study the brain by manipulating it and recording from it using surgical and electrical methods. In this module, you will learn how psychopharmacologists manipulate the brain and record from it using chemical methods.

The major research strategy of psychopharmacology is to administer drugs that either increase or decrease the effects of particular neurotransmitters and to observe the behavioral consequences. Described here are routes of drug administration, methods of using chemicals to make selective brain lesions, methods of measuring the chemical activity of the brain that are particularly useful in biopsychological research, and methods for locating neurotransmitter systems.

Routes of Drug Administration

LO 5.13 Describe the various methods of drug administration.

In most psychopharmacological experiments, drugs are administered in one of the following ways: (1) they are fed to the subject; (2) they are injected through a tube into the stomach (*intragastrically*); or (3) they are injected hypodermically into the peritoneal cavity of the abdomen (*intraperitoneally, IP*), into a large muscle (*intramuscularly, IM*), into the fatty tissue beneath the skin (*subcutaneously, SC*), or into a large surface vein (*intravenously, IV*). A problem with these peripheral routes of administration is that many drugs do not readily pass through the blood–brain barrier. To overcome this problem, drugs can be administered in small amounts through a fine, hollow tube, called a **cannula**, that has been stereotaxically implanted in the brain.

Selective Chemical Lesions

LO 5.14 Describe the method of selective neurotoxic lesions.

The effects of surgical, radio-frequency, and reversible lesions are frequently difficult to interpret because they affect all neurons in the target area. In some cases, it is possible to make more selective lesions by injecting **neurotoxins** (neural poisons) that have an affinity for certain components of the nervous system. There are many selective neurotoxins. For example, when either *kainic acid* or *ibotenic acid* is administered by microinjection, it is preferentially taken up by cell bodies at the tip of the cannula and destroys those neurons, while leaving neurons with axons passing through the area largely unscathed.

Another selective neurotoxin that has been widely used is *6-hydroxydopamine* (*6-OHDA*). It is taken up by only those neurons that release the neurotransmitter *norepinephrine* or *dopamine*, and it leaves other neurons at the injection site undamaged.

Measuring Chemical Activity of the Brain

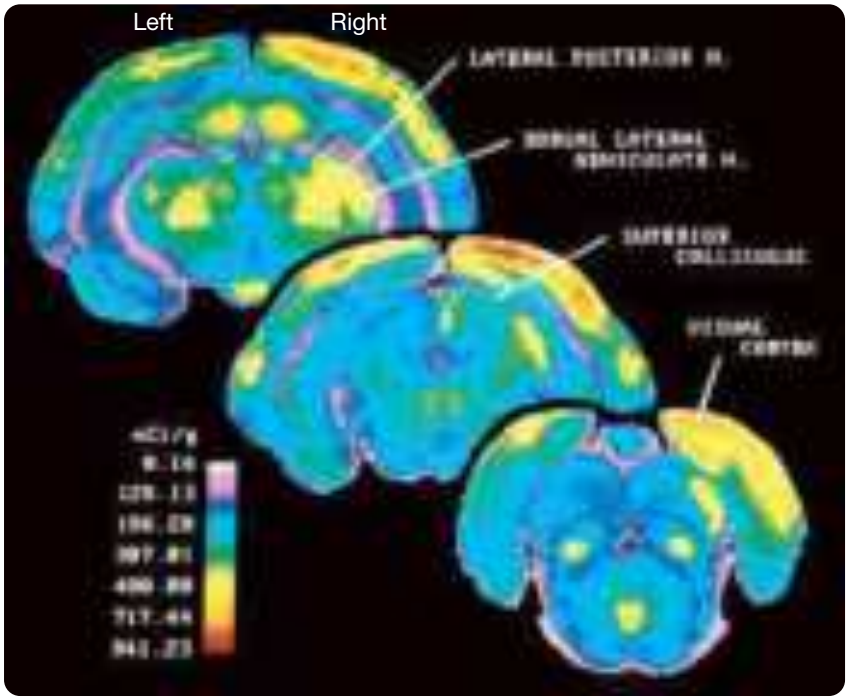
LO 5.15 Describe two techniques for measuring chemical activity in the brain.

There are many procedures for measuring the chemical activity of the brains of laboratory animals. Two techniques that have proved particularly useful in biopsychological research are the 2-deoxyglucose technique and cerebral dialysis.

2-DEOXYGLUCOSE TECHNIQUE. The *2-deoxyglucose* (*2-DG*) *technique* entails placing an animal that has been injected with radioactive 2-DG in a test situation in which it engages in an activity of interest. Because 2-DG is similar in structure to glucose—the brain's main source of energy—neurons active during the test absorb it at a high rate but do not metabolize it. Then the subject is killed, and its brain is removed and sliced. The slices are then subjected to **autoradiography**: They are coated with a photographic emulsion, stored in the dark for a few days, and then developed much like film. Areas of the brain that absorbed high levels of radioactive 2-DG during the test appear as black spots on the slides. The density of the spots in various regions of the brain can then be color-coded (see Figure 5.18).

CEREBRAL DIALYSIS. **Cerebral dialysis** is a method of measuring the extracellular concentration of specific neurochemicals in behaving animals (most other techniques for measuring neurochemicals require that the subjects be killed so that tissue can be extracted). Cerebral dialysis involves implanting a fine tube with a short semipermeable

Figure 5.18 The 2-deoxyglucose technique. The accumulation of radioactivity is shown in three frontal sections taken from the brain of a Richardson's ground squirrel. The subject was injected with radioactive 2-deoxyglucose; then, for 45 minutes, it viewed brightly illuminated black and white stripes through its left eye while its right eye was covered. Because the ground squirrel visual system is largely crossed, most of the radioactivity accumulated in the visual structures of the right hemisphere.



Rod Cooper/University of Calgary Department of Psychology

section into the brain. The semipermeable section is positioned in the brain structure of interest so that extracellular chemicals from the structure will diffuse into the tube. Once in the tube, they can be collected for freezing, storage, and later analysis; or they can be carried in solution directly to a *chromatograph* (a device for measuring the chemical constituents of liquids or gases).

Locating Neurotransmitters and Receptors in the Brain

LO 5.16 Describe two techniques for locating particular neurotransmitters or receptors in the brain.

A key step in trying to understand the psychological function of a particular neurotransmitter or receptor is finding out where it is located in the brain. Two of the techniques available for this purpose are immunocytochemistry and in situ hybridization. Each involves exposing brain slices to a labeled *ligand* of the molecule under investigation (the ligand of a molecule is another molecule that binds to it).

IMMUNOCYTOCHEMISTRY. When a foreign protein (an *antigen*) is injected into an animal, the animal's body creates *antibodies* that bind to it and help the body remove or destroy it; this is known as the body's *immune reaction*. Neurochemists have created stocks of antibodies for the brain's peptide neurotransmitters (neuropeptides) and their receptors. **Immunocytochemistry** is a procedure for locating particular neuroproteins in the brain by labeling their antibodies with a dye or radioactive element and then exposing slices of brain tissue to the labeled antibodies. Regions of dye or radioactivity accumulation in the brain slices mark the locations of the target neuroprotein.

Because all enzymes are proteins and because only those neurons that release a particular neurotransmitter are likely to contain all the enzymes required for its synthesis, immunocytochemistry can be used to locate neurotransmitters by binding to their enzymes. This is done by exposing brain slices to labeled antibodies that bind to enzymes located in only those neurons that contain the neurotransmitter of interest (see Figure 5.19).

Figure 5.19 Immunocytochemistry. This section through a rat's pons reveals noradrenergic neurons that have attracted the antibody for dopamine-beta-hydroxylase, the enzyme that converts dopamine to norepinephrine.

Richard Mooney, University of Toledo College of Medicine, Department of Neurosciences

IN SITU HYBRIDIZATION. Another technique for locating peptides and other proteins in the brain is **in situ hybridization**. This technique takes advantage of the fact that all peptides and proteins are transcribed from sequences of nucleotide bases on strands of messenger RNA (mRNA). The nucleotide base sequences that direct the synthesis of many neuroproteins have been identified, and hybrid strands of mRNA with the complementary base sequences have been artificially created. In situ hybridization involves the following steps. First, hybrid RNA strands with the base sequence complementary to that of the mRNA that directs the synthesis of the target neuroprotein are obtained. Next, the hybrid RNA strands are labeled with a dye or radioactive element. Finally, the brain slices are exposed to the labeled hybrid RNA strands; they bind to the complementary mRNA strands, marking the location of neurons that release the target neuroprotein.

Genetic Methods

Genetics is a science that has made amazing progress, and biopsychologists are reaping the benefits. Modern genetic methods are now widely used in biopsychological research, which just a few decades ago would have seemed like science fiction. These genetic methods allow

for adding, removing, and altering specific genes. There are three categories of genetic methods: (1) gene knockout techniques, (2) gene knockin techniques, and (3) gene editing techniques.

Gene Knockout Techniques

LO 5.17 Explain the gene knockout technique by describing an experiment that employed the technique.

Gene knockout techniques are procedures for creating organisms that lack a particular gene under investigation (e.g., Gingras et al., 2014). Mice (the favored mammalian subjects of genetic research) that are the products of gene knockout techniques are referred to as *knockout mice*. (This term often makes us smile, as images of little mice with boxing gloves flit through our minds.)

Many gene knockout studies have been conducted to clarify the neural mechanisms of behavior. For example, Ruby and colleagues (2002) and Hattar and colleagues (2003) used *melanopsin knockout mice* (mice in whom the gene for the synthesis of melanopsin has been deleted) to study the role of melanopsin in regulating the light–dark cycles that control circadian (about 24 hours) rhythms of bodily function—for example, daily cycles of sleep, eating, and body temperature. *Melanopsin* is a protein found in some neurons in the mammalian *retina* (the receptive layer of the eye), and it had been implicated in the control of circadian rhythms by light. Knockout of the gene for synthesizing melanopsin impaired, but did not eliminate, the ability of mice to adjust their circadian rhythms in response to changes in the light–dark cycle. Thus, melanopsin appears to contribute to the control of circadian rhythms by light, but it is not the only factor.

This type of result is typical of gene knockout studies of behavior: Many genes have been discovered that contribute to particular behaviors, but invariably other mechanisms are involved. It may be tempting to think that each behavior is controlled by a single gene, but the reality is much more complex. Each behavior is controlled by many genes interacting with one another and with experience through *epigenetic mechanisms* (see Chapter 2).

Gene Knockin Techniques

LO 5.18 Explain the gene knockin technique by describing an experiment that employed the technique.

It is now possible to replace one gene with another or add a gene that doesn't exist in an organism. Such **gene knockin techniques** have created interesting possibilities for research and therapy. Pathological genes from human cells can be inserted in other animals such as mice—mice that contain the genetic material of another species are called **transgenic mice**. For example, Shen and colleagues (2008) created transgenic mice by inserting a defective human gene that had been found to be associated with schizophrenia in a Scottish family with a particularly high incidence of the condition. The transgenic mice displayed a variety of cerebral abnormalities (e.g., reduced cerebral cortex and enlarged ventricles) and atypical behaviors reminiscent of human schizophrenia. Treating neurological disease by replacing faulty genes in patients suffering from genetic disorders is an exciting, but as yet unrealized, goal.

Gene Editing Techniques

LO 5.19 Describe how modern gene editing techniques, such as the CRISP-Cas9 method, can provide better ways of assessing the role of a gene in behavior.

Many genes that contribute to particular behaviors have been discovered, but invariably other mechanisms are involved. It may be tempting to think that each behavior is controlled by a single gene, but the reality is much more complex. Each behavior is controlled by many genes interacting with one another and with experience over the course of development (i.e., through epigenetic mechanisms; see Chapter 2).

As a means of controlling for the interaction of genes with experience, many researchers now use modern **gene editing techniques**. These new gene editing techniques allow researchers to edit genes at a particular time during development (see Heidenreich & Zhang, 2016; Khan, 2019).

Of the many gene editing techniques currently available, the **CRISPR/Cas9 method** is generating the most excitement (see Adli, 2018; Luo, Callaway, & Svoboda, 2018). In the most widely used version of the CRISPR/Cas9 method, Cas9 (a protein) is linked to a strand of RNA called the *guide-RNA*. The guide-RNA is made up of a sequence of nucleotide bases that are complementary to one or more strands of DNA. Once the guide-RNA and Cas9 are linked, it can be integrated into a virus. The virus can then be injected into an animal—either peripherally if one wants to edit the genome of the whole organism, or intracranially into a specific brain region if one wants to observe the focal effects of editing a gene in cells in that brain region.

Once the virus enters a cell, and the guide-RNA lines up with a complementary strand of DNA in the organism, Cas9 can either inhibit or activate the genes through various mechanisms. Furthermore, Cas9 can be regulated in various ways so that a researcher can control the effects of Cas9 on *gene expression* (see Chapter 2); thus, a researcher can reversibly alter the expression of a gene (or

set of genes) in a particular brain region and examine the effects on behavior. Cas9 can also be used to alter an organism's *epigenome* (see Chapter 2)—see Gomez, Beitnere, and Segal, 2019.

Fantastic Fluorescence and the Brainbow

LO 5.20 Explain how green fluorescent protein has been used as a research tool in the neurosciences.

Green fluorescent protein (GFP) is a protein that exhibits bright green fluorescence when exposed to blue light. First isolated by Shimomura, Johnson, and Saiga (1962), from a species of jellyfish found off the west coast of North America, GFP is currently stimulating advances in many fields of biological research. Martin Chalfie, Osamu Shimomura, and Roger Tsien were awarded the 2008 Nobel Prize in chemistry for its discovery and study.

The utility of GFP as a research tool in the biological sciences could not be realized until its gene was identified and cloned in the early 1990s. The general strategy is to activate the GFP gene in only the particular cells under investigation so that they can be readily visualized. This can be accomplished in two ways: by inserting the GFP gene in only the target cells or by introducing the GFP gene in all cells of the subject but expressing the gene in only the target cells. Chalfie and colleagues (1994) were the first to use GFP to visualize neurons. They introduced the GFP gene into a small transparent roundworm, *Caenorhabditis elegans*, in an area of its chromosomes that controls the development of touch receptor neurons. Figure 5.20 shows the glowing touch receptor neurons. The GFP gene has now been expressed in the cells of many plant and animal species, including humans.

Livet and colleagues (2007) took the very useful GFP technique one step further—one big step. First, Tsien (1998) found that making minor alterations to the GFP gene resulted in the synthesis of proteins that fluoresced in different colors. Livet and colleagues (2007) then introduced the mutated genes for cyan, yellow, and blue fluorescent proteins into the genomes of developing mice in such a way that they were expressed in developing neurons. Each neuron produced different amounts of the three proteins, giving it a distinctive color—in the same way that a color printer can make any color by mixing only three colored inks in differing proportions. Because each neuron was labeled with its own distinctive color, the pathways of neural axons could be traced to their destinations through the cellular morass. This technique has been dubbed **brainbow** for obvious reasons—see Figure 5.21.

In addition to making brainbows, fluorescent proteins have allowed researchers to (1) label specific neurotransmitters so their activity can be observed (see Wang, Jing, & Li, 2018), (2) label synaptic vesicle proteins in order to observe the fusion of synaptic vesicles with the presynaptic membrane (see Deo & Lavis, 2018), (3) visualize postsynaptic potentials (see Chapter 4) by using fluorescent proteins that light up during membrane hyperpolarizations or depolarizations, and (4) observe the binding of neurotransmitters to receptors by creating receptors that light up when they bind their transmitter (see Lin & Schnitzer, 2016; Storace et al., 2016).

Figure 5.20 Touch receptor neurons of the transparent *Caenorhabditis elegans* labeled by green fluorescent protein.

Chalfie, M., et. al. (1994). Green fluorescent protein as a marker for gene expression. Science, 263(5148), 802-805. Used with permission from American Association for the Advancement of Science (AAAS).

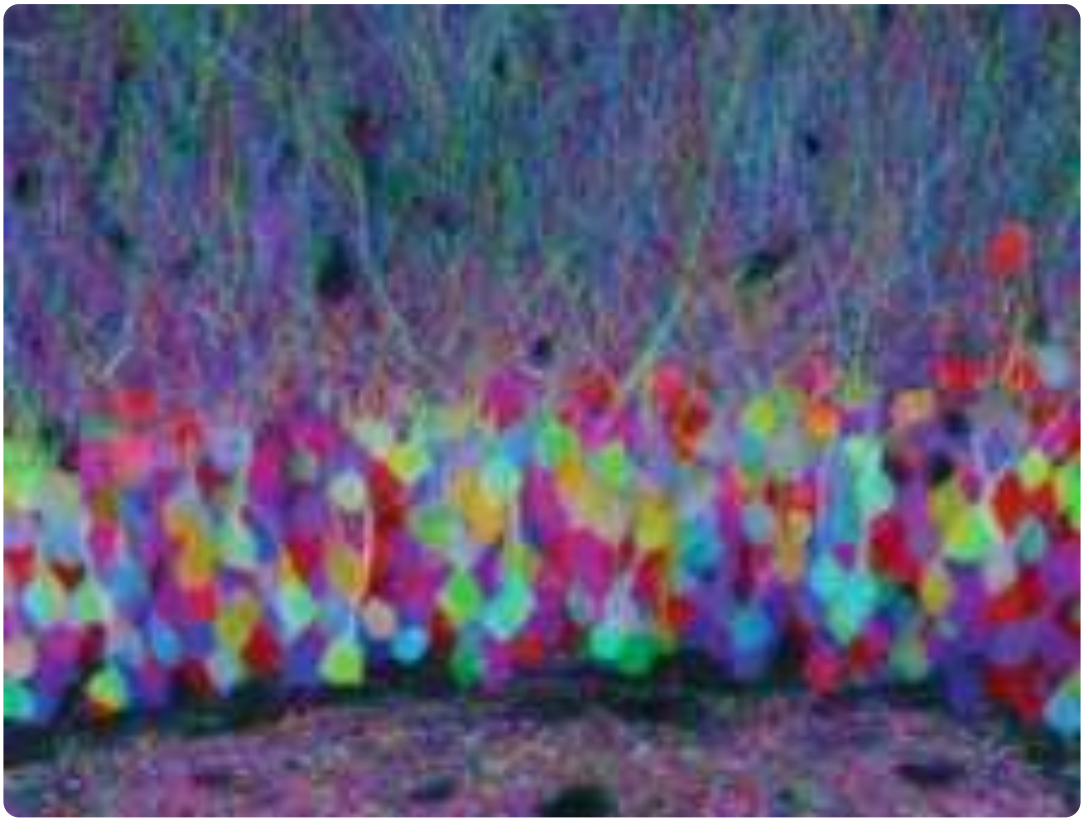
Optogenetics: A Neural Light Switch

LO 5.21 Explain how opsins have been used as a research tool in the neurosciences.

Opsins are light-sensitive ion channels that are found in the cell membranes of certain bacteria and algae (see Boyden, 2014). When opsins are illuminated with light, they open and allow ions to enter the cell. Depending on the particular opsin, light can either hyperpolarize or depolarize the cell membrane they are embedded in. The use of opsins is currently revolutionizing how neuroscientists study the brain (see Boyden, 2015; Kim, Adhikari, & Deisseroth, 2017; Paoletti, Ellis-Davies, & Mourot, 2019).

The utility of opsins for neuroscience research couldn't be realized until their gene was identified and rendered into a form that was expressible within a mammalian cell—a feat that was first accomplished in 2003 (see Boyden, 2014). Soon thereafter, neuroscientists started to use genetic engineering techniques to insert the opsin gene, or variants of the opsin gene, into particular types of neurons. In effect, by inserting an opsin gene into a particular type of neuron, a neuroscientist could use light to hyperpolarize or depolarize

Figure 5.21 With the research technique called *brainbow*, each neuron is labeled with a different color, facilitating the tracing of neural axons.



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neurons. This novel method is known as **optogenetics** (see Goshen, 2014; Paoletti, Ellis-Davies, & Mourot, 2019; Yuste & Church, 2014), and it is increasingly being used by many neuroscientists (see Berndt & Deisseroth, 2015). For example, it can be used in living animals by injecting the animal with a virus carrying an opsin gene that targets a particular type of neuron (e.g., dopaminergic neurons; see Chang et al., 2016). An optical fiber can then be implanted in the animal and light can be shone through the fiber (see Paoletti, Ellis-Davies, & Mourot, 2019; Pisanello et al., 2017) to activate the opsin ion channels—causing the activity of only specific neurons to either be increased or suppressed (see Wiegert et al., 2017). Recent advances have allowed for the use of optogenetics in freely moving animals through the use of wireless technology (see Gutruf & Rogers, 2018).

Scan Your Brain

The research methods of biopsychology illustrate a psychological disorder suffered by many scientists. We call it "unabbreviaphobia"—the fear of leaving any term unabbreviated. To determine whether you have mastered Part One of this chapter and are ready for Part Two, supply the full term for each of the following abbreviations. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your incorrect answers and omissions.

1. CT: _____
2. MRI: _____
3. PET: _____
4. 2-DG: _____
5. fMRI: _____
6. MEG: _____
7. TMS: _____
8. EEG: _____
9. ERP: _____
10. AEP: _____
11. EMG: _____
12. EOG: _____

13. SCL: _____
14. SCR: _____
15. ECG: _____
16. EKG: _____
17. IP: _____
18. IM: _____
19. IV: _____
20. SC: _____
21. 6-OHDA: _____
22. GFP: _____
23. fUS: _____
24. tES: _____

Scan Your Brain answers: (1) computed tomography, (2) magnetic resonance imaging, (3) positron emission tomography, (4) 2-deoxyglucose, (5) functional MRI, (6) magnetoencephalography, (7) transcranial magnetic stimulation, (8) electroencephalogram, (9) event-related potential, (10) average evoked potential, (11) electromyogram, (12) electrooculogram, (13) skin conductance level, (14) skin conductance response, (15) electrocardiogram, (16) electrocardiogram, (17) intraperitoneal, (18) intramuscular, (19) intravenous, (20) subcutaneous, (21) 6-hydroxydopamine, (22) green fluorescent protein, (23) functional ultrasound imaging, (24) transcranial electrical stimulation

PART TWO Behavioral Research Methods of Biopsychology

We turn now from methods used by biopsychologists to study the nervous system to those that deal with the behavioral side of biopsychology. Because of the inherent invisibility of neural activity, the primary objective of the methods used in its investigation is to render the unobservable observable. In contrast, the major objectives of behavioral research methods are to control, to simplify, and to objectify.

A single set of procedures developed for the investigation of a particular behavioral phenomenon is commonly referred to as a **behavioral paradigm**. Each behavioral paradigm normally comprises a method for producing the behavioral phenomenon under investigation and a method for objectively measuring it.

Neuropsychological Testing

A patient suspected of suffering from some sort of nervous system dysfunction is usually referred to a *neurologist*, who assesses simple sensory and motor functions. More subtle changes in perceptual, emotional, motivational, or cognitive functions are the domain of the *neuropsychologist*.

Because neuropsychological testing is so time consuming, it is typically prescribed for only a small portion of brain-damaged patients. This is unfortunate; the results of neuropsychological testing can help brain-damaged patients in three important ways: (1) by assisting in the diagnosis of neural disorders, particularly in cases in which brain imaging, EEG, and neurological testing have proved equivocal; (2) by serving as a basis for counseling and caring for the patients; and (3) by providing a basis for objectively evaluating the effectiveness of a treatment or the seriousness of its side effects.

Modern Approach to Neuropsychological Testing

LO 5.22 Describe three approaches to neuropsychological testing.

The nature of neuropsychological testing has changed radically since the 1950s. Indeed, the dominant approach to psychological testing has evolved through three distinct phases: the *single-test approach*, the *standardized-test-battery approach*, and the modern *customized-test-battery approach*.

THE SINGLE-TEST APPROACH. Before the 1950s, the few existing neuropsychological tests were designed to detect the presence of brain damage; in particular, the goal of these early tests was to discriminate between patients with psychological problems resulting from structural brain damage and those with psychological problems resulting from functional, rather than structural, changes to the brain. This approach proved unsuccessful, in large part because no single test could be developed that would be sensitive to all the varied and complex psychological symptoms that could potentially occur in a brain-damaged patient.

THE STANDARDIZED-TEST-BATTERY APPROACH. The standardized-test-battery approach to neuropsychological testing grew out of the failures of the single-test approach, and by the 1960s, it became predominant in North America. The objective stayed the same—to identify brain-damaged patients—but the testing involved *standardized batteries* (sets) of tests rather than a single test. The most widely used standardized test battery has been the *Halstead-Reitan Neuropsychological Test Battery*. The Halstead-Reitan is a set of tests that tend to be performed poorly by brain-damaged

patients in relation to other patients or healthy controls; the scores on each test are added together to form a single aggregate score. An aggregate score below the designated cutoff leads to a diagnosis of brain damage. The standardized-test-battery approach proved only marginally successful; standardized test batteries discriminate effectively between neurological patients and healthy individuals, but they are not so good at discriminating between neurological patients and psychiatric patients.

THE CUSTOMIZED-TEST-BATTERY APPROACH. The customized-test-battery approach—an approach largely developed by Luria and other Soviet Union neuropsychologists (see Ardila, 1992; Luria & Majovski, 1977)—began to be used routinely in a few American neuropsychological research institutions in the 1960s. This approach proved highly successful in research, and it soon spread to clinical practice. It now predominates in both the research laboratory and the neurological ward.

The objective of current neuropsychological testing is not merely to identify patients with brain damage; the objective is to characterize the nature of the psychological deficits of each brain-damaged patient. So how does the customized-test-battery approach to neuropsychological testing work? It usually begins in the same way for all patients: with a common battery of tests selected by the neuropsychologist to provide an indication of the general nature of the neuropsychological symptoms. Then, depending on the results of the common test battery, the neuropsychologist selects a series of tests customized to each patient in an effort to characterize in more detail the general symptoms revealed by the common battery. For example, if the results of the test battery indicated that a patient had a memory problem, subsequent tests would include those designed to reveal the specific nature of the memory problem.

The tests used in the customized-test-battery approach differ in three respects from earlier approaches. First, the newer tests are specifically designed to measure aspects of psychological function that have been spotlighted by modern theories and data. For example, modern theories, and the evidence on which they are based, suggest that the mechanisms of short-term and long-term memory are totally different; thus, the testing of patients with memory problems virtually always involves specific tests of both short-term and long-term memory. Second, the interpretation of the test results often does not rest entirely on how well the patient does; unlike early neuropsychological tests, currently used tests often require the neuropsychologist to assess the cognitive strategy that the patient employs in performing the test. Third, the customized-test-battery approach requires more skill and knowledge on the part of the neuropsychologist to select just the right battery of tests to expose a particular patient's deficits and to identify qualitative differences in cognitive strategy.

Tests of the Common Neuropsychological Test Battery

LO 5.23 Describe those tests that are often administered as part of an initial common neuropsychological test battery.

Because the customized-test-battery approach to neuropsychological testing typically involves two phases—a battery of general tests given to all patients followed by a series of specific tests customized to each patient—we'll cover examples of these neuropsychological tests in two sections. In this section, we'll look at some tests that are often administered as part of the initial common test battery.

INTELLIGENCE. Although the overall *intelligence quotient* (*IQ*) is a notoriously poor measure of brain damage, a test of general intelligence is nearly always included in the battery of neuropsychological tests routinely given to all patients. Many neuropsychological assessments begin with the **Wechsler Adult Intelligence Scale (WAIS)**, first published in 1955 and standardized in 1981 on a sample of 1,880 U.S. citizens between 16 and 71. The WAIS is composed of many subtests and is often the first test administered, because knowing a patient's IQ can help a neuropsychologist interpret the results of subsequent tests. Also, a skilled neuropsychologist can sometimes draw inferences about a patient's neuropsychological dysfunction from the pattern of deficits on the subtests of the WAIS. For example, low scores on subtests of verbal comprehension tend to be associated with left hemisphere damage.

MEMORY. One weakness of the WAIS is that it often fails to detect memory deficits, despite including subtests specifically designed to test memory function. For example, the information subtest of the WAIS assesses memory for general knowledge (e.g., "Who is Queen Elizabeth?"), and the **digit span** subtest (the most widely used test of short-term memory) identifies the longest sequence of random digits that a patient can repeat correctly 50 percent of the time; most people have a digit span of 7. However, these two forms of memory are among the least likely to be disrupted by brain damage—patients with seriously disturbed memory function often show no deficits on either the information or the digit span subtest. Be that as it may, memory problems rarely escape unnoticed because they are usually reported by the patient or the family of the patient.

LANGUAGE. If a neuropsychological patient has taken the WAIS, deficits in the use of language can be inferred from a low aggregate score on the verbal subtests. A patient who has not taken the WAIS can be quickly screened for language-related deficits with the **token test**. Twenty tokens of two different shapes (squares and circles), two different sizes (large and small), and five different colors (white, black, yellow, green, and red) are placed on a table in front of the patient. The test begins with the examiner reading simple

instructions—for example, "Touch a red square"—and the patient trying to follow them. Then the test progresses to more difficult instructions, such as "Touch the small, red circle and then the large, green square." Finally, the patient is asked to read the instructions aloud and follow them.

LANGUAGE LATERALIZATION. It is usual for one hemisphere to participate more than the other in language-related activities. In most people, the left hemisphere is dominant for language, but in some, the right hemisphere is dominant. A test of language lateralization is often included in the common test battery because knowing which hemisphere is dominant for language is often useful in interpreting the results of other tests. Furthermore, a test of language lateralization is virtually always given to patients before any surgery that might encroach on the cortical language areas. The results are used to plan the surgery, trying to avoid the language areas if possible.

There are two widely used tests of language lateralization. The sodium amytal test (Wada, 1949) is one and the dichotic listening test (Kimura, 1973) is the other.

The **sodium amytal test** involves injecting the anesthetic *sodium amytal* into either the left or right carotid artery in the neck. This temporarily anesthetizes the *ipsilateral* (same-side) hemisphere while leaving the *contralateral* (opposite-side) hemisphere largely unaffected. Several tests of language function are quickly administered while the ipsilateral hemisphere is anesthetized. Later, the process is repeated for the other side of the brain. When the injection is on the side dominant for language, the patient is completely mute for about 2 minutes. When the injection is on the nondominant side, there are only a few minor speech problems. Because the sodium amytal test is invasive, it can be administered only for medical reasons—usually to determine the dominant language hemisphere prior to brain surgery.

In the standard version of the **dichotic listening test**, sequences of spoken digits are presented to volunteers through stereo headphones. Three digits are presented to one ear at the same time that three different digits are presented to the other ear. Then, they are asked to report as many of the six digits as they can. Kimura (1973) found that patients correctly report more of the digits heard by the ear contralateral to their dominant hemisphere for language, as determined by the sodium amytal test.

Tests of Specific Neuropsychological Function

LO 5.24 Describe tests that might be used by a neuropsychologist to investigate in more depth general problems revealed by a common neuropsychological test battery.

Following analysis of the results of a neuropsychological patient's performance on a common test battery, the neuropsychologist selects a series of specific tests to clarify the nature of the general problems exposed by the common battery. There are thousands of tests that might be selected from. This section describes a few of them and mentions some of the considerations that might influence their selection.

Journal Prompt 5.2

What are some of the clinical implications of this two-stage approach to neuropsychological testing?

MEMORY. Following the discovery of memory impairment by the common test battery, at least four fundamental questions about the memory impairment must be answered (see Chapter 11): (1) Does the memory impairment involve *short-term memory*, *long-term memory*, or both? (2) Are any deficits in long-term memory *anterograde* (affecting the retention of things learned after the damage), *retrograde* (affecting the retention of things learned before the damage), or both? (3) Do any deficits in long-term memory involve *semantic memory* (memory for knowledge of the world) or *episodic memory* (memory for personal experiences)? (4) Are any deficits in long-term memory deficits of *explicit memory* (memories of which the patient is aware and can thus express verbally), *implicit memory* (memories demonstrated by the improved performance of the patient without the patient being conscious of them), or both?

Many amnesic patients display severe deficits in explicit memory with no deficits at all in implicit memory (see Squire & Dede, 2015). **Repetition priming tests** have proven instrumental in the assessment and study of this pattern. Patients are first shown a list of words and asked to study them; they are not asked to remember them. Then, at a later time, they are asked to complete a list of word fragments, many of which are fragments of words from the initial list. For example, if "purple" had been in the initial test, "pu_p_ _" could be one of the test word fragments. Amnesic patients often complete the fragments as accurately as healthy control subjects. But—and this is the really important part—they often have no conscious memory of any of the words in the initial list or even of ever having seen the list. In other words, they display good implicit memory of experiences without explicit memories of them.

LANGUAGE. If a neuropsychological patient turns out to have language-related deficits on the common test battery, a complex series of tests is administered to clarify the nature of the problem. For example, if a patient has a speech problem, it may be one of three fundamentally different problems: problems of *phonology* (the rules governing the sounds of the language), problems of *syntax* (the grammar of the language), or problems of *semantics* (the meaning of the language). Because brain-damaged patients may have

one of these problems but not the others, it is imperative that the testing of all neuropsychological patients with speech problems include tests of each of these three capacities.

Reading aloud can be disrupted in different ways by brain damage, and follow-up tests must be employed that can differentiate between the different patterns of disruption. Some *dyslexic* patients (those with reading problems) remember the rules of pronunciation but have difficulties pronouncing words that do not follow these rules, words such as *come* and *tongue*, whose pronunciation must be remembered. Other dyslexic patients pronounce simple familiar words based on memory but have lost the ability to apply the rules of pronunciation—they cannot pronounce nonwords such as *trapple* or *fleeming*.

Behavioral Methods of Cognitive Neuroscience

The Case of the Vegetative Patient

What if a patient in a vegetative state was in fact completely conscious but simply unable to generate an observable response to stimuli? Owen and colleagues (2014) asked this precise question. They set about studying patients in a *vegetative state*. While in an MRI scanner, they instructed one of their patients to visualize each of two things: (1) playing tennis and (2) navigating through her home, room-to-room; each of these tasks was known to activate a distinct set of brain regions in healthy control participants. Amazingly, she displayed patterns of activation on her fMRI that were remarkably similar to what had been observed in controls. Shocked by this finding, Owen and colleagues wanted to see if they could communicate with the patient. To do so, while undergoing fMRI they instructed her to visualize playing tennis to say "yes" and to visualize walking around her home to say "no." Then, they asked her some questions for which they knew the answers (e.g., "Is your father's name Karlis?"). She responded with the correct answer to each of their questions—faint whispers from a trapped mind.

This case study is just one example of the powerful things that functional imaging is capable of. In this module you will learn about the techniques that *cognitive neuroscientists* use to study relationships between brain and cognition.

As we warned you earlier in this chapter, it is important to think critically about the results of functional brain imaging studies (see Raz, 2012). Because fMRI images are so compelling, it is particularly important to be an informed consumer of them; to understand the assumptions and research methods of **cognitive neuroscience:** a division of biopsychology that focuses on understanding cognition.

Before we present the behavioral methods of cognitive neuroscience, let's first discuss two key assumptions that are common in cognitive neuroscience. The first assumption is that each complex cognitive process results from the combined activity of simple cognitive processes called **constituent cognitive processes**. The second assumption is that each constituent cognitive process is mediated by neural activity within a particular brain region or across a set of brain regions (see Sporns & Betzel, 2016). Accordingly, the main goal of cognitive neuroscience is to identify the parts of the brain that mediate various constituent cognitive processes.

Paired-Image Subtraction Technique

LO 5.25 Describe the paired-image subtraction technique.

With the central role played by PET and fMRI in cognitive neuroscience research, the **paired-image subtraction technique** has become one of the key behavioral research methods in such research (see Kriegeskorte, 2010; Posner & Raichle, 1994). Let us illustrate this technique with the classic PET study of single-word processing by Petersen and colleagues (1988). Petersen and his colleagues were interested in locating the parts of the brain that enable a person to make a word association (to respond to a printed word by saying a related word). You might think this would be an easy task to accomplish by having a volunteer perform a word-association task while a PET image of the volunteer's brain is recorded. The problem with this approach is that many parts of the brain that would be active during the test period would have nothing to do with the constituent cognitive process of forming a word association; much of the activity recorded would be associated with other processes such as seeing the words, reading the words, and speaking. The paired-image subtraction technique was developed to deal with this problem.

The paired-image subtraction technique involves obtaining functional brain images during several different cognitive tasks. Ideally, the tasks are designed so that pairs of them differ from each other in terms of only a single constituent cognitive process. Then the brain activity associated with that process can be estimated by subtracting the activity in the image associated with one of the two tasks from the activity in the image associated with the other. For example, in one of the tasks in the study by Petersen and colleagues, volunteers spent a minute reading aloud printed nouns as they appeared on a screen; in another, they observed the same nouns on the screen but responded to each of them by saying aloud an associated verb (e.g., *truck—drive*). Then Petersen and his colleagues subtracted the activity in the images they recorded during the two tasks to obtain a *difference image*. The difference image

illustrated the areas of the brain specifically involved in the constituent cognitive process of forming the word association; the activity associated with fixating on the screen, seeing the nouns, saying the words, and so on, was eliminated by the subtraction.

Default Mode Network

LO 5.26 Understand the default mode network and know the structures that are part of that network.

Interpretation of difference images is complicated by the fact that there is substantial brain activity when humans sit quietly and let their minds wander—this level of activity has been termed the brain's **default mode** (Raichle, 2010). Brain structures typically active in the default mode but less active during cognitive or behavioral tasks are collectively referred to as the **default mode network,** and their pattern of activity is known as the **resting state-fMRI (R-fMRI)**. The default mode network comprises many structures (see Fox et al., 2015) including the following four cortical areas: medial parietal cortex, lateral parietal cortex, medial prefrontal cortex, and lateral temporal cortex. See Figure 5.22.

Mean Difference Images

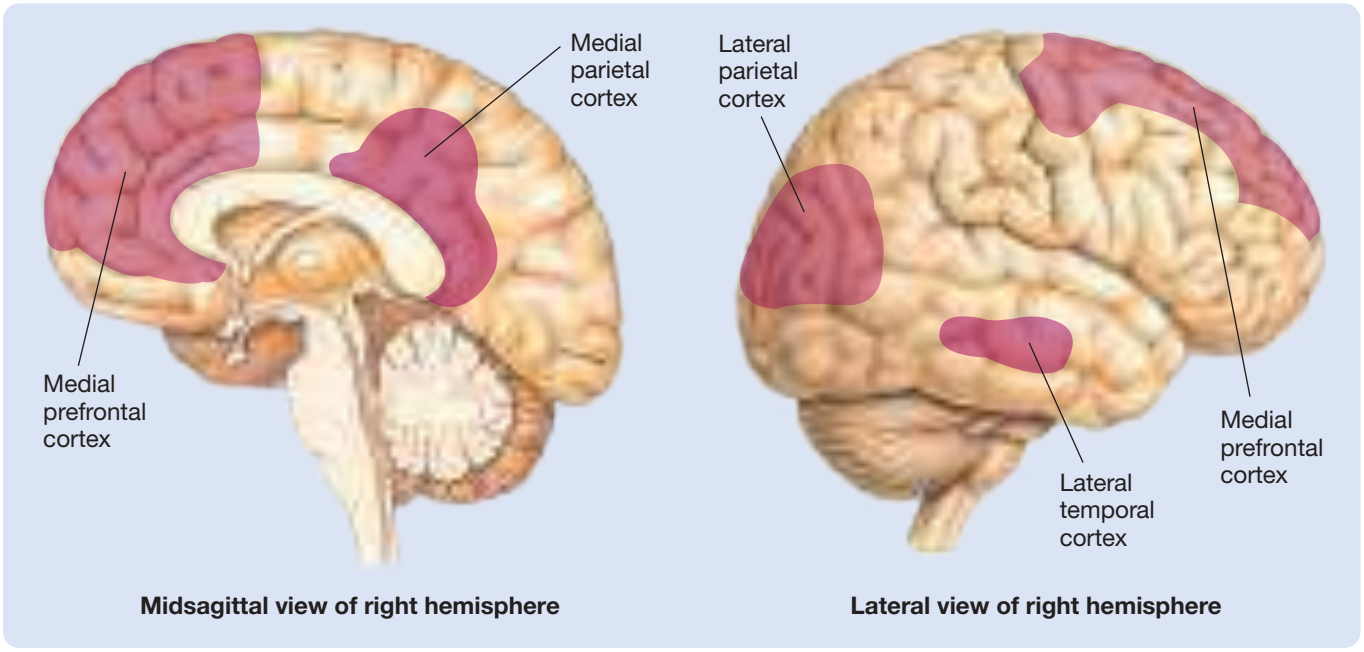
LO 5.27 Explain what a mean difference image is.

Another difficulty in using PET and fMRI to locate constituent cognitive processes results from the *noise* associated with random cerebral events that occur during the test—for example, thinking about a sudden pang of hunger, noticing a fly on the screen, or wondering whether the test will last much longer (see Mason et al., 2007). The noise created by such events can be significantly reduced with a technique discussed earlier in this chapter: *signal averaging*. By averaging the difference images obtained from repetitions of the same tests, the researchers can greatly increase the *signal-to-noise ratio*. It is standard practice to average the images obtained from several volunteers; the resulting **mean** (averaged) **difference image** emphasizes areas of activity that are common to many volunteers and de-emphasizes areas of activity that are peculiar to a few of them. However, this averaging procedure can lead to at least two serious problems. First, if two volunteers had specific but different patterns of cortical activity, the average image derived from the two would reveal little about either. Because people differ substantially from one another in the cortical localization of cognitive abilities, this is a serious problem (see Braver, Cole, & Yarkoni, 2010; Kanai & Rees, 2011; Lichtman & Denk, 2011). Second, the area of cortex that controls a particular ability could change in an individual as a result of experience.

Journal Prompt 5.3

If an area of cortex that controls a particular ability can change in an individual based on their experiences, what implications, if any, does this neuroplasticity have for the reliability and validity of mean difference images?

Figure 5.22 The default mode network: areas of the brain in which activity is commonly recorded by functional brain-imaging techniques when the mind wanders, but not when it is actively engaged.



Functional Connectivity

LO 5.28 Explain the concept of functional connectivity.

In addition to being interested in which brain regions are active during particular cognitive tasks, cognitive neuroscientists are also eager to understand how network activity across multiple brain regions is related to a particular cognitive task. This approach is referred to as the study of **functional connectivity (FC)**. To measure functional connectivity, a cognitive neuroscientist examines which brain regions have parallel patterns of activity over time.

When a cognitive neuroscientist studies changes in FC with the presentation of a stimulus, or during the performance of a task, they are studying *extrinsic FC*. This is in contrast to *intrinsic FC*, which is FC that is present during the R-fMRI (see Kelly & Castellanos, 2014). Collectively, the task of characterizing the FC associated with each behavior and cognitive process is known as the study of the **functional connectome** (see Matthews & Hampshire, 2016).

Biopsychological Paradigms of Animal Behavior

Noteworthy examples of the behavioral paradigms used to study the biopsychology of laboratory species are provided here under three headings: (1) paradigms for the assessment of species-common behaviors, (2) traditional conditioning paradigms, and (3) seminatural animal learning paradigms. In each case, the focus is on methods used to study the behavior of the laboratory rat, one of the most common subjects of biopsychological research.

Paradigms for the Assessment of Species-Common Behaviors

LO 5.29 Describe three behavioral paradigms used to study species-common behaviors.

Many of the behavioral paradigms used in biopsychological research are used to study species-common behaviors. **Species-common behaviors** are those displayed by virtually all members of a species, or at least by all those of the same age and sex. Commonly studied species-common behaviors include grooming, swimming, eating, drinking, copulating, fighting, and nest building. Described here are the open-field test, tests of aggressive and defensive behavior, and tests of sexual behavior.

OPEN-FIELD TEST. In the **open-field test**, the subject is placed in a large, barren chamber, and its activity is recorded (see Brooks & Dunnett, 2009). It is also common in the open-field test to count the number of *boluses* (pieces of excrement) that were dropped by an animal during the test. Low activity scores and high bolus counts are frequently used as indicators of fearfulness. Fearful rats are also highly **thigmotaxic**; that is, they rarely venture away from the walls of the test chamber and rarely engage in such activities as rearing and grooming. Rats are often fearful when they are first placed in a strange open field, but this fearfulness usually declines with repeated exposure to the same open field.

TESTS OF AGGRESSIVE AND DEFENSIVE BEHAVIOR. Typical patterns of aggressive and defensive behavior can be observed and measured during combative encounters between the dominant male rat of an established colony and a smaller male intruder (see Blanchard & Blanchard, 1988). This is called the **colony-intruder paradigm**. The behaviors of the dominant male are considered to be aggressive and those of the hapless intruder defensive. The dominant male of the colony (the *alpha male*) moves sideways toward the intruder, with its hair erect. When it nears the intruder, it tries to push the intruder off balance and to deliver bites to its back and flanks. The defender tries to protect its back and flanks by rearing up on its hind legs and pushing the attacker away with its forepaws or by rolling onto its back. Thus, piloerection, lateral approach, and flank- and back-biting indicate conspecific aggression in the rat; freezing, boxing (rearing and pushing away), and rolling over indicate defensiveness.

Some tests of rat defensive behavior assess reactivity to the experimenter rather than to another rat. For example, it is common to rate the resistance of a rat to being picked up—no resistance being the lowest category and biting the highest—and to use the score as one measure of defensiveness.

The **elevated plus maze**, a four-armed, plus-sign-shaped maze typically mounted 50 centimeters above the floor, is a test of defensiveness commonly used to study the *anxiolytic* (anxiety-reducing) effects of drugs. Two of the arms of the maze have sides, and two do not. The measure of defensiveness, or anxiety, is the proportion of time the rats spend in the protected closed arms rather than on the exposed arms. Many established anxiolytic drugs significantly increase the proportion of time that rats spend on the open arms, and new drugs that prove to be effective in reducing rats' defensiveness on the maze often turn out to be effective in the treatment of human anxiety.

TESTS OF SEXUAL BEHAVIOR. Most attempts to study the physiological bases of rat sexual behavior have focused on the copulatory act itself. The male mounts the female from behind and clasps her hindquarters. If the female is receptive, she responds by assuming the posture called

lordosis; that is, she sticks her hindquarters in the air, she bends her back in a U, and she deflects her tail to the side. During some mounts, the male inserts his penis into the female's vagina; this act is called **intromission**. After intromission, the male dismounts by jumping backward. He then returns a few seconds later to mount and intromit once again. Following about 10 such cycles of mounting, intromitting, and dismounting, the male mounts, intromits, and **ejaculates** (ejects his sperm).

Three common measures of male rat sexual behavior are the number of mounts required to achieve intromission, the number of intromissions required to achieve ejaculation, and the interval between ejaculation and the reinitiation of mounting. The most common measure of female rat sexual behavior is the **lordosis quotient** (the proportion of mounts that elicit lordosis).

Traditional Conditioning Paradigms

LO 5.30 Describe the Pavlovian conditioning paradigm and the operant conditioning paradigm.

Learning paradigms play a major role in biopsychological research for three reasons. The first is that learning is a phenomenon of primary interest to psychologists. The second is that learning paradigms provide an effective technology for producing and controlling animal behavior. Because animals cannot follow instructions from the experimenter, it is often necessary to train them to behave in a fashion consistent with the goals of the experiment. The third reason is that it is possible to infer much about the sensory, motor, motivational, and cognitive state of an animal from its ability to learn and perform various responses.

If you have taken a previous course in psychology, you will likely be familiar with the Pavlovian and operant conditioning paradigms. In the **Pavlovian conditioning paradigm**, the experimenter pairs an initially neutral stimulus called a *conditional stimulus* (e.g., a tone or a light) with an *unconditional stimulus* (e.g., meat powder)—a stimulus that elicits an *unconditional* (reflexive) *response* (e.g., salivation). As a result of these pairings, the conditional stimulus eventually acquires the capacity, when administered alone, to elicit a *conditional response* (e.g., salivation)—a response that is often, but not always, similar to the unconditional response.

In the **operant conditioning paradigm**, the rate at which a particular voluntary response (such as a lever press) is emitted is increased by *reinforcement* or decreased by *punishment*. One widely used operant conditioning paradigm in biopsychology is the self-stimulation paradigm. In the **self-stimulation paradigm**, animals press a lever to deliver electrical stimulation to particular sites in their own brains; those structures in the brain that support self-stimulation have often been called *pleasure centers*.

Seminatural Animal Learning Paradigms

LO 5.31 Describe four seminatural animal learning paradigms.

In addition to Pavlovian and operant conditioning paradigms, biopsychologists use animal learning paradigms that have been specifically designed to mimic situations that an animal might encounter in its natural environment. Development of these paradigms stemmed in part from the reasonable assumption that forms of learning tending to benefit an animal's survival in the wild are likely to be more highly developed and more directly related to innate neural mechanisms. The following are four common seminatural learning paradigms: conditioned taste aversion, radial arm maze, Morris water maze, and conditioned defensive burying.

CONDITIONED TASTE AVERSION. A **conditioned taste aversion** is the avoidance response that develops to tastes of food whose consumption has been followed by illness (see Garcia & Koelling, 1966; Lin, Arthurs, & Reilly, 2014). In the standard conditioned taste aversion experiment, rats receive an *emetic* (a nausea-inducing drug) after they consume a food with an unfamiliar taste. On the basis of this single conditioning trial, the rats learn to avoid the taste.

The ability of rats to readily learn the relationship between a particular taste and subsequent illness unquestionably increases their chances of survival in their natural environment, where potentially edible substances are not routinely screened by government agencies. Rats and many other animals are *neophobic* (afraid of new things); thus, when they first encounter a new food, they consume it in only small quantities. If they subsequently become ill, they will not consume it again. Conditioned aversions also develop to familiar tastes, but these typically require more than a single trial to be learned.

Humans also develop conditioned taste aversions. Cancer patients have been reported to develop aversions to foods consumed before nausea-inducing chemotherapy (Bernstein & Webster, 1980). Many of you will be able to testify on the basis of personal experience about the effectiveness of conditioned taste aversions. I (JP) still have vivid memories of a batch of red laboratory punch that I overzealously consumed after eating two pieces of blueberry pie. But that is another story—albeit a particularly colorful one.

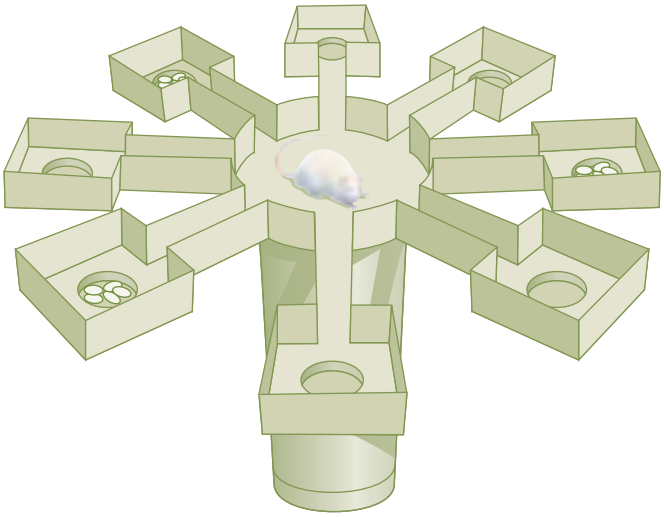
The discovery of conditioned taste aversion challenged three widely accepted principles of learning (see Revusky & Garcia, 1970) that had grown out of research on traditional operant and Pavlovian conditioning paradigms. First, it challenged the view that animal conditioning is always a gradual step-by-step process; robust taste aversions can be established in only a single trial. Second, it showed that

temporal contiguity is not essential for conditioning; rats acquire taste aversions even when they do not become ill until several hours after eating. Third, it challenged the *principle of equipotentiality*—the view that conditioning proceeds in basically the same manner regardless of the particular stimuli and responses under investigation. Rats appear to have evolved to readily learn associations between tastes and illness; it is only with great difficulty that they learn relations between the color of food and nausea or between taste and footshock.

RADIAL ARM MAZE. The radial arm maze taps into the well-developed spatial abilities of rodents. The survival of rats in the wild depends on their ability to navigate quickly and accurately through their environment and to learn which locations in it are likely to contain food and water. This task is much more complex for a rodent than it is for us. Most of us obtain food from locations where the supply is continually replenished; we go to the market confident that we will find enough food to satisfy our needs. In contrast, the foraging rat must learn and retain a complex pattern of spatially coded details. It must not only learn where morsels of food are likely to be found but must also remember which of these sites it has recently stripped of their booty so as not to revisit them too soon. Designed by Olton and Samuelson (1976) to study these spatial abilities, the **radial arm maze** (see Figure 5.23) is an array of arms—usually eight or more—radiating from a central starting area. At the end of each arm is a food cup, which may or may not be baited, depending on the purpose of the experiment.

In one version of the radial arm maze paradigm, rats are placed each day in a maze that has the same arms baited each day. After a few days of experience, rats rarely visit unbaited arms at all, and they rarely visit baited arms more than once in the same day—even when control procedures make it impossible for them to recognize odors left during previous visits to an arm or to make their visits in a systematic sequence. Because the arms are identical, rats must orient themselves in the maze with reference to external room cues; thus, their performance can be disrupted by rotation of the maze or by changes in the appearance of the room.

Figure 5.23 A radial arm maze.



MORRIS WATER MAZE. Another seminatural learning paradigm that has been designed to study the spatial abilities of rats is the **Morris water maze** (Morris, 1981). The rats are placed in a circular, featureless pool of cool milky water in which they must swim until they discover the escape platform—which is invisible just beneath the surface of the water. The rats are allowed to rest on the platform before being returned to the water for another trial. Despite the fact that the starting point is varied from trial to trial, the rats learn after only a few trials to swim directly to the platform, presumably by using spatial cues from the room as a reference. The Morris water maze is useful for assessing the navigational skills of brain-lesioned or drugged animals.

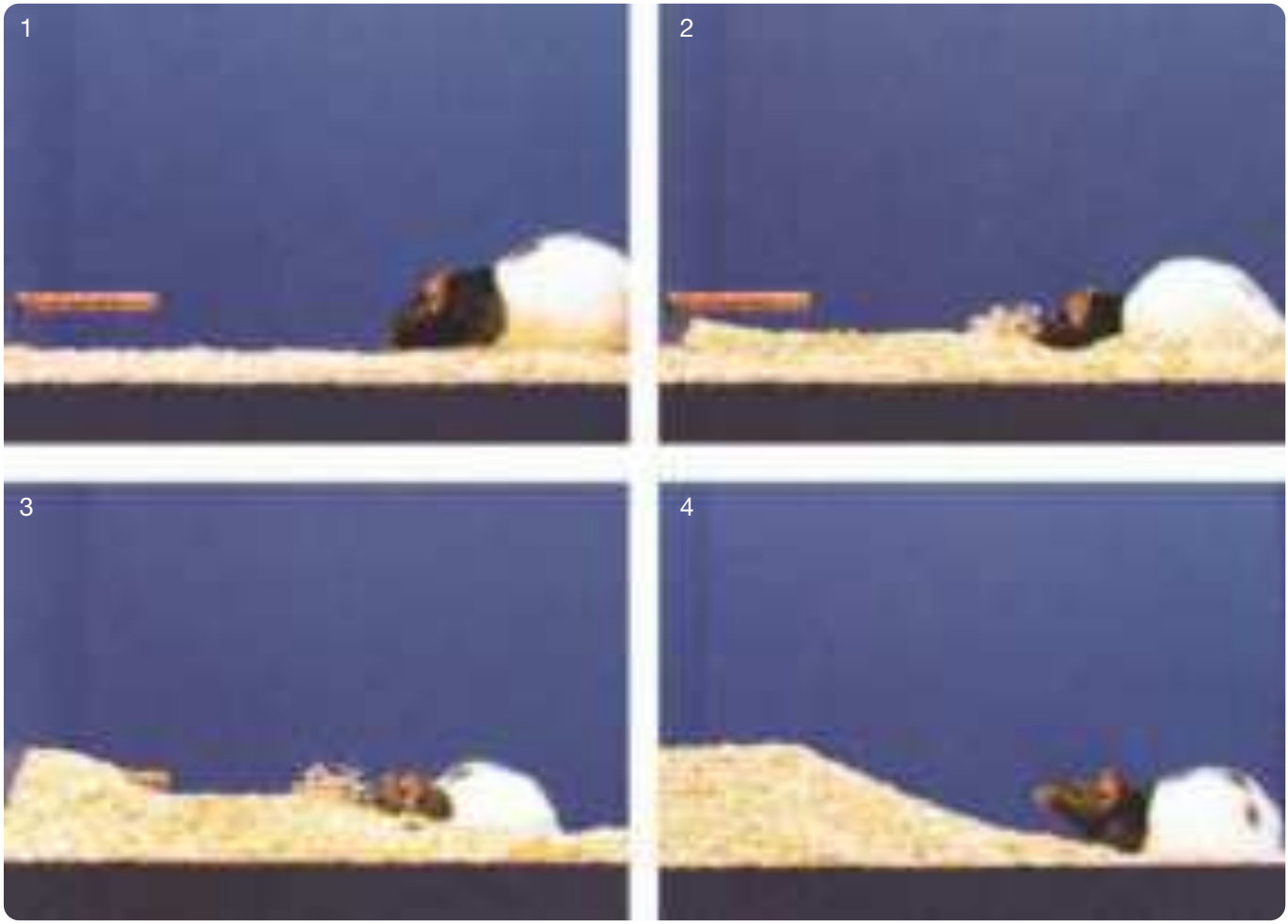
CONDITIONED DEFENSIVE BURYING. Yet another seminatural learning paradigm useful in biopsychological research is conditioned defensive burying (e.g., Pinel & Mana, 1989; Pinel & Treit, 1978). In studies of **conditioned defensive burying**, rats receive a single aversive stimulus (e.g., a shock, air blast, or noxious odor) from an object mounted on the wall of the chamber just above the floor, which is littered with bedding material. After a single trial, almost every rat learns that the test object is a threat and responds by flinging bedding material at the test object with its head and forepaws (see Figure 5.24). Antianxiety drugs reduce the amount of conditioned defensive burying, and thus the paradigm is used to study the neurochemistry of anxiety (see Steimer, 2011).

Thinking Creatively About Biopsychological Research

LO 5.32 Explain why multiple techniques should be used when trying to answer a specific question.

Before moving on to the next chapter, you need to appreciate that multiple research methods almost always need to be used to answer a question; seldom, if ever, is an important biopsychological issue resolved by use of a single method. The reason for this is that neither the methods used to manipulate the brain nor the methods used to assess the behavioral consequences of these manipulations are totally selective; there are no methods of manipulating the brain that change only a single aspect of brain function, and there are no measures of behavior that reflect only a single psychological process. Accordingly, lines of research that use a single method can usually be

Figure 5.24 These photos show a rat burying a test object from which it has just received a single mild shock.



John Pinel

interpreted in more than one way and thus cannot provide unequivocal evidence for any one interpretation. Typically, important research questions are resolved only when several methods are brought to bear on a single problem. This general approach, as you may recall, is called *converging operations*.

Journal Prompt 5.4

Think of a research question that would require converging operations (i.e., using several methods to address a single problem) among two or more of the research methods described in this chapter.

Themes Revisited

This chapter introduced you to the two kinds of research methods used by biopsychologists: methods of studying the brain and methods of studying behavior. In the descriptions of these methods, all five of the main themes of the text were apparent.

The chapter-opening case of Professor P. alerted you to the fact that many of the methods used by biopsychologists to study the human brain are also used clinically, in either diagnosis or treatment. The clinical implications theme came up again during discussions of brain imaging, genetic engineering, neuropsychological testing, and use of the elevated plus maze to test anxiolytic drugs.

The thinking creatively theme was implicit throughout this entire chapter. That is, a major purpose of this chapter was to help you better understand the research methods of biopsychology so you can be an informed consumer of biopsychological research. Moreover, the development of new research methods often requires considerable creativity.

The neuroplasticity theme arose during the discussion of the methods of cognitive neuroscience. Experience can

produce changes in brain organization that can complicate the interpretation of functional brain images.

The evolutionary perspective theme arose in the discussion of green fluorescent protein, first isolated from jellyfish, and again during the discussion of the rationale for using seminatural animal learning paradigms, which assess animal behavior in environments similar to those in which it evolved.

Only one of the emerging themes appeared in this chapter. The thinking about epigenetics theme appeared only briefly during the discussion of modern tools for editing an animal's genome.

Key Terms

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Methods of Visualizing and Stimulating the Living Human Brain

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Cerebral angiography, p. 124
Computed tomography (CT), p. 124
Positron emission tomography (PET), p. 125
Fluorodeoxyglucose (FDG), p. 125
Ligands, p. 125
Magnetic resonance imaging (MRI), p. 125
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Chapter 6
The Visual System

How We See

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Chapter Overview and Learning Objectives

Light Enters the Eye and Reaches the Retina	**LO 6.1** Explain how the pupil and the lens can affect the image that falls on the retina.
	LO 6.2 Explain why some vertebrates have one eye on each side of their head, whereas other vertebrates have their eyes mounted side-by-side on the front of their heads. Also, explain the importance of binocular disparity.
The Retina and Translation of Light into Neural Signals	**LO 6.3** Describe the structure of the retina and name the cell types that make up the retina.
	LO 6.4 Describe the duplexity theory of vision and explain the differences between the photopic and scotopic systems.
	LO 6.5 Explain the difference between the photopic and scotopic spectral sensitivity curves and explain how that difference can account for the Purkinje effect.

	LO 6.6 Describe the three types of involuntary fixational eye movements and explain what happens when all eye movements are blocked.
	LO 6.7 Describe the process of visual transduction.
From Retina to Primary Visual Cortex	**LO 6.8** Describe the components and layout of the retina-geniculate-striate system.
	LO 6.9 In the context of the retina-geniculate-striate system, explain what is meant by retinotopic.
	LO 6.10 Describe the M and P channels.
Seeing Edges	**LO 6.11** Describe contrast enhancement.
	LO 6.12 Define the term *receptive field* and describe the methods used by David Hubel and Torsten Wiesel to map the receptive fields of visual system neurons.
	LO 6.13 Describe the work of Hubel & Wiesel that helped to characterize the receptive fields of retinal ganglion cells, lateral geniculate neurons, and striate neurons of lower layer IV.
	LO 6.14 Describe the work of Hubel & Wiesel that characterized the receptive fields of simple and complex cells in the primary visual cortex.
	LO 6.15 Describe the organization of the primary visual cortex.
	LO 6.16 Describe how views about the receptive fields of retinal ganglion cells and lateral geniculate neurons have recently changed.
	LO 6.17 Describe the changing view of visual system receptive fields.
Seeing Color	**LO 6.18** Describe the component and opponent-process theories of color vision.
	LO 6.19 Describe Land's demonstration of color constancy and explain his retinex theory.
Cortical Mechanisms of Vision and Conscious Awareness	**LO 6.20** Describe the three classes of visual cortex and identify their locations in the brain.
	LO 6.21 Explain what happens when an area of primary visual cortex is damaged.
	LO 6.22 Describe the areas of secondary visual cortex and association cortex involved in vision.
	LO 6.23 Explain the difference between the dorsal and ventral streams and the functions that have been attributed to each stream by different theories.
	LO 6.24 Describe the phenomenon of prosopagnosia and discuss the associated theoretical issues.
	LO 6.25 Describe the phenomenon of akinetopsia and discuss the associated theoretical issues.

This chapter is about your visual system. Most people think their visual system has evolved to respond as accurately as possible to the patterns of light that enter their eyes. They recognize the obvious limitations in the accuracy of their visual system, of course; and they appreciate those curious instances, termed *visual illusions*, in which it is "tricked" into seeing things the way they aren't. But such shortcomings are generally regarded as minor imperfections in a system that responds as faithfully as possible to the external world.

But, despite the intuitive appeal of thinking about it in this way, this is not how the visual system works. The visual system does not produce an accurate internal copy of the external world. It does much more. From the tiny, distorted, upside-down, two-dimensional retinal images projected on the visual receptors that line the backs of the eyes, the visual system creates an accurate, richly detailed, three-dimensional perception that is—and this is the really important part—in some respects even better than the external reality from which it was created. Our primary goal in this chapter is to help you appreciate the inherent creativity of your own visual system.

You will learn in this chapter that understanding the visual system requires the integration of two types of research: (1) research that probes the visual system with sophisticated neuroanatomical, neurochemical, and neurophysiological techniques; and (2) research that focuses on the assessment of what we see. Both types of research receive substantial coverage in this chapter, but it is the second type that provides you with a unique educational opportunity: the opportunity to participate in the very research you are studying. Throughout this chapter, you will be encouraged to participate in a series of Check It Out demonstrations designed to illustrate the relevance of what you are learning in this text to life outside its pages.

This chapter is composed of six modules. The first three take you on a journey from the external visual world to the visual receptors of the retina and from there over the major visual pathway to the primary visual cortex. The next two modules describe how the neurons of this visual pathway mediate the perception of two particularly important features of the visual world: edges and color. The final module deals with the flow of visual signals from the primary visual cortex to other parts of the cortex that participate in the complex process of vision.

Before you begin the first module of the chapter, we'd like you to consider an interesting clinical case. Have you ever wondered whether one person's subjective experiences are like those of others? This case provides evidence that at least some of them are. It was reported by Whitman Richards (1971), and his participant was his wife. Mrs. Richards suffered from migraine headaches (see Goadsby, 2015), and like 20 percent of migraine sufferers, she often experienced visual displays, called *fortification illusions*, prior to her attacks (see Charles & Baca, 2013; Thissen et al., 2014).

The Case of Mrs. Richards: Fortification Illusions and the Astronomer

Each fortification illusion began with a gray area of blindness near the center of her visual field—see Figure 6.1. During the next few minutes, the gray area would begin to expand into a horseshoe shape, with a zigzag pattern of flickering lines at its advancing edge (this pattern reminded people of the plans for a fortification, hence the name of the illusions).

It normally took about 20 minutes for the lines and the trailing area of blindness to reach the periphery of her visual field. At this point, her headache would usually begin.

Because the illusion expanded so slowly, Mrs. Richards was able to stare at a point on the center of a blank sheet of paper and periodically trace on the sheet the details of her illusion. This method made it apparent that the lines became thicker and the expansion of the area of blindness occurred faster as the illusion spread into the periphery.

Interestingly, Dr. Richards discovered that a similar set of drawings was published in 1870 by the famous British astronomer George Biddell Airy. They were virtually identical to those done by Mrs. Richards.

Figure 6.1 The fortification illusions associated with migraine headaches.

1 An attack begins, often when reading, as a gray area of blindness near the center of the visual field.

2 Over the next 20 minutes, the gray area assumes a horseshoe shape and expands into the periphery, at which point the headache begins.

We will return to fortification illusions after you have learned a bit about the visual system. At that point, you will be better able to appreciate their significance.

Light Enters the Eye and Reaches the Retina

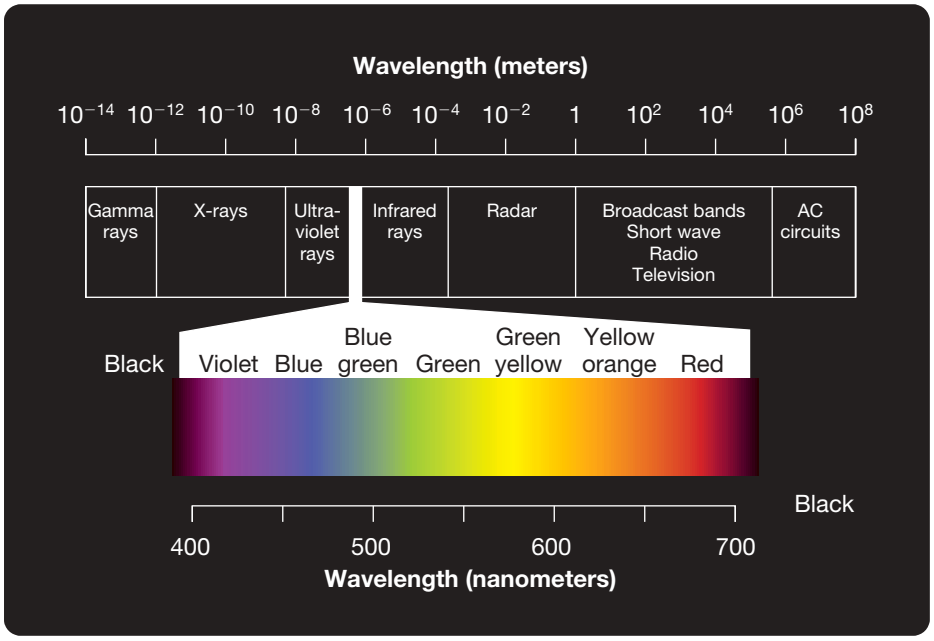
Everybody knows that cats, owls, and other nocturnal animals can see in the dark. Right? Wrong! Some animals have special adaptations that allow them to see under very dim illumination, but no animal can see in complete darkness. The light reflected into your eyes from the objects around you is the basis for your ability to see them; if there is no light, there is no vision.

You may recall from high-school physics that light can be thought of in two different ways: as discrete particles of energy, called *photons*, traveling through space at about 300,000 kilometers (186,000 miles) per second, or as waves of energy. Both theories are useful; in some ways, light behaves like particles; and in others, it behaves like waves. Physicists have learned to live with this nagging inconsistency, and we must do the same.

Light is sometimes defined as waves of electromagnetic energy between 380 and 760 *nanometers* (billionths of a meter) in length (see Figure 6.2). There is nothing special about these wavelengths except that the human visual system responds to them. In fact, some animals can see wavelengths that we cannot (see Gehring, 2014). For example, rattlesnakes can see *infrared waves*, which are too long for humans to see; as a result, they can see warm-blooded prey in what for us would be complete darkness. So, if we were writing this text for rattlesnakes, we would be forced to provide a different definition of light for them.

Wavelength and intensity are two properties of light that are of particular interest—wavelength because it plays an important role in the perception of color, and intensity because it plays an important role in the perception of brightness. In everyday language, the concepts of *wavelength* and *color* are often used interchangeably, as are *intensity* and *brightness*. For example, we commonly refer to an intense light with a wavelength of 700 nanometers as being a bright red light (see Figure 6.2), when in fact it is our perception of the light, not the light itself, that is bright and red. We know that these distinctions may seem trivial to you now, but by the end of the chapter you will appreciate their importance.

Figure 6.2 The electromagnetic spectrum and the colors that had been associated with wavelengths visible to humans.



Pupil and Lens

LO 6.1 **Explain how the pupil and the lens can affect the image that falls on the retina.**

The amount of light reaching the *retinas* is regulated by the donut-shaped bands of contractile tissue, the *irises*, which give our eyes their characteristic color (see Figure 6.3). Light enters the eye through the *pupil*, the hole in the iris. The adjustment of pupil size in response to changes in illumination represents a compromise between

Figure 6.3 The human eye. Light enters the eye through the pupil, whose size is regulated by the iris. The iris gives the eye its characteristic color—blue, brown, or other.

tarapong srichaiyos/Shutterstock

sensitivity (the ability to detect the presence of dimly lit objects) and **acuity** (the ability to see the details of objects). When the level of illumination is high and sensitivity is thus not important, the visual system takes advantage of the situation by constricting the pupils. When the pupils are constricted, the image falling on each retina is sharper and there is a greater *depth of focus*; that is, a greater range of depths is simultaneously kept in focus on the retinas. However, when the level of illumination is too low to adequately activate the receptors, the pupils dilate to let in more light, thereby sacrificing acuity and depth of focus.

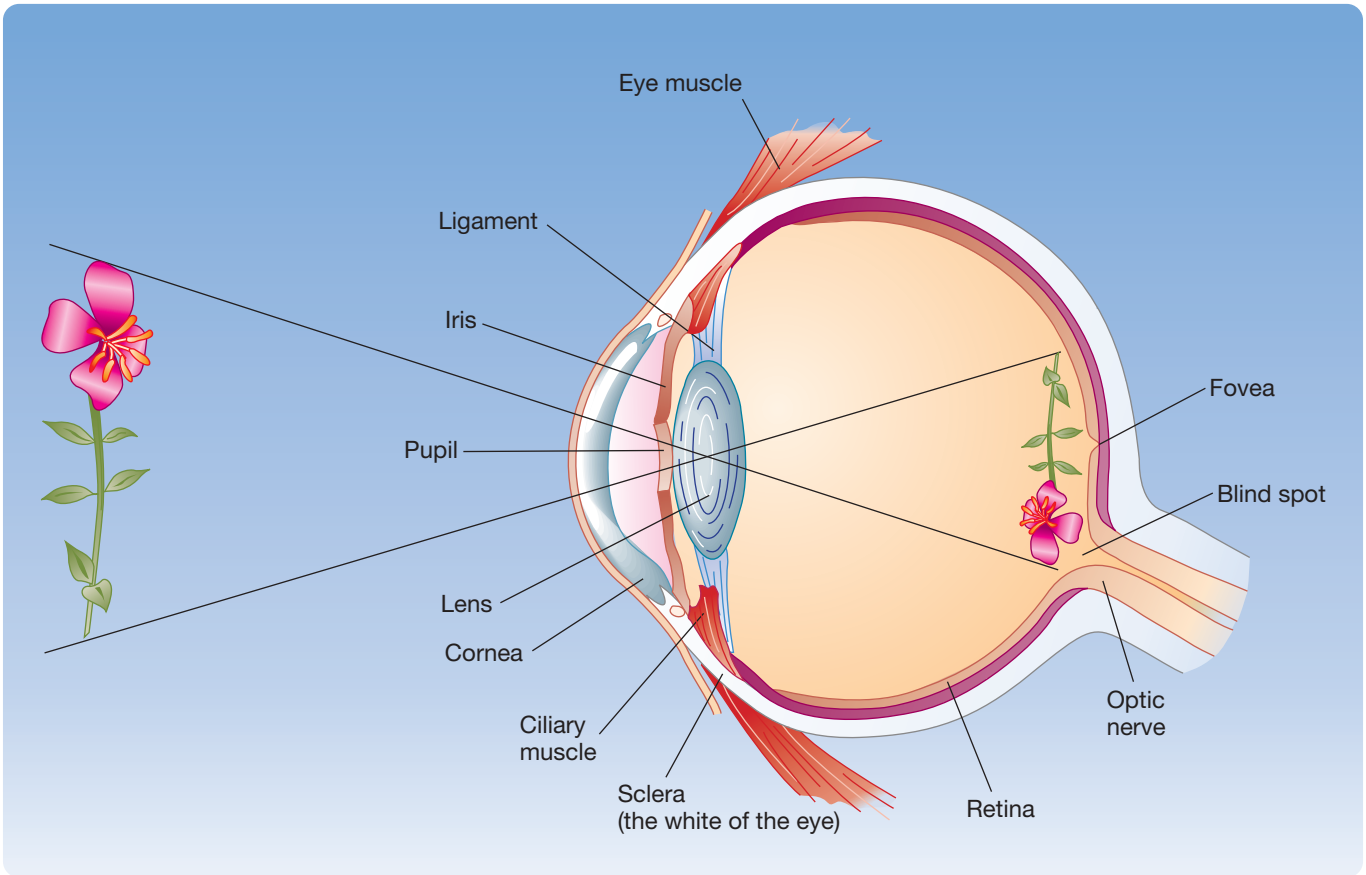
Behind each pupil is a *lens*, which focuses incoming light on the retina (see Figure 6.4). When we direct our gaze at something near, the tension on the ligaments holding each lens in place is adjusted by the **ciliary muscles**, and the lens assumes its natural cylindrical shape. This increases the ability of the lens to *refract* (bend) light and thus brings close objects into sharp focus. When we focus on a distant object, the lens is flattened. The process of adjusting the configuration of the lenses to bring images into focus on the retina is called **accommodation**.

Eye Position and Binocular Disparity

LO 6.2 **Explain why some vertebrates have one eye on each side of their head, whereas other vertebrates have their eyes mounted side-by-side on the front of their heads. Also, explain the importance of binocular disparity.**

No description of the eyes of vertebrates would be complete without a discussion of their most obvious feature: the fact that they come in pairs. One reason vertebrates have two eyes is that vertebrates have two sides: left and right. By having one eye on each side, which is by far the most common arrangement, vertebrates can see in almost every direction without moving their heads. But then why do some vertebrates, including humans, have their eyes mounted side-by-side on the front of their heads? (See the first Check It Out demonstration on the next page.) This arrangement sacrifices the ability to see behind so that what is in front can be viewed through both eyes simultaneously—an arrangement that is an important basis for our visual system's ability to create three-dimensional perceptions (to see depth) from two-dimensional retinal images (see Baden, Euler, & Berens, 2020).

Figure 6.4 The human eye, a product of approximately 600 million years of evolution.



Based on Lamb, T. D., Collin, S. P., & Pugh, E. N. (2007). Evolution of the vertebrate eye: Opsins, photoreceptors, retina and eye cup. *Nature Reviews Neuroscience*, 8, 960–975.

Journal Prompt 6.1

Why do you think the two-eyes-on-the-front arrangement has evolved in some species but not in others? (After you've written your answer, see the first Check It Out demonstration below for more on this issue.)

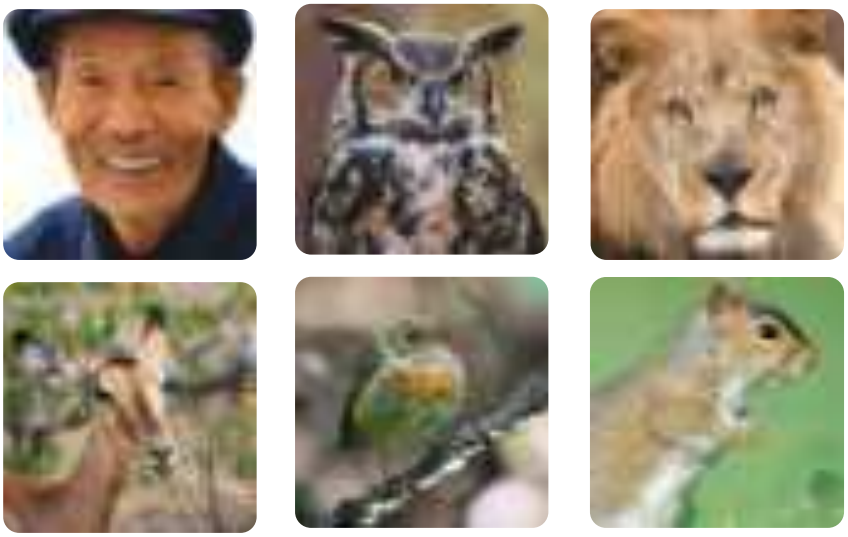
The movements of your eyes are coordinated so that each point in your visual world is projected to corresponding points on your two retinas. To accomplish this, your eyes must *converge* (turn slightly inward); convergence is greatest when you are inspecting things that are close. But the positions of the images on your two retinas can never correspond exactly because your two eyes do not view the world from exactly the same position. **Binocular disparity**—the difference in the position of the same image on the two retinas—is greater for close objects than for distant objects; therefore, your visual system can use the degree of binocular disparity to construct one three-dimensional perception from two two-dimensional retinal images (see Lappin, 2014). (Look at the second Check It Out demonstration below.)

Check It Out

The Position of Eyes

Here you see three animals whose eyes are on the front of their heads (a human, an owl, and a lion) and three whose eyes are on the sides of their heads (an antelope, a canary, and a squirrel). Why do a few vertebrate species have their eyes side-by-side on the front of the head while most species have one eye on each side?

In general, predators tend to have the front-facing eyes because this enables them to accurately perceive how far away prey animals are; prey animals tend to have side-facing eyes because this gives them a larger field of vision and the ability to see predators approaching from most directions.



Top row from left: Guiziou Franck/Hemis/Alamy Stock Photo; Matthew Cuda/Alamy Stock Photo; C.K. Lorenz/Science Source
Bottom row from left: Naomi Engela Le Roux/123RF; Vasiliy Vishnevskiy/123RF; Colin Varndell/Nature Picture Library

Check It Out

Binocular Disparity and the Mysterious Cocktail Sausage

If you compare the views from each eye (by quickly closing one eye and then the other) of objects at various distances in front of you—for example, your finger held at different distances—you will notice that the disparity between the two views is greater for closer objects. Now try the mysterious demonstration of the cocktail sausage. Face the farthest wall in the room (or some other distant object) and bring the tips of your two pointing fingers together at arm's length in front of you—with the backs of your fingers away from you (unless you prefer sausages with fingernails). Now, with both eyes open, look through the notch between your touching fingertips, but focus on the wall. Do you see the cocktail sausage between your fingertips? Where did it come from? To prove to yourself that the sausage is a product of binocularity, make it disappear by shutting one eye. Warning: Do not eat this sausage.

The Retina and Translation of Light into Neural Signals

After light passes through the pupil and the lens, it reaches the retina. The retina converts light to neural signals, conducts them toward the CNS, and participates in the processing of the signals (Hoon et al., 2014; Seung & Sümbül, 2014).

Structure of the Retina

LO 6.3 **Describe the structure of the retina and name the cell types that make up the retina.**

Figure 6.5 illustrates the fundamental cellular structure of the retina. The retina is composed of five different types of neurons: **receptors**, **horizontal cells**, **bipolar cells**, **amacrine cells**, and **retinal ganglion cells**. Each of these five types of retinal neurons comes in a variety of subtypes: More than 60 different kinds of retinal neurons have been identified (see Cepko, 2015; Seung & Sümbül, 2014), including about 30 different retinal ganglion cells (see Baden et al., 2016). Notice that the amacrine cells and the horizontal cells are specialized for *lateral communication* (communication across the major channels of sensory input). Retinal neurons communicate both chemically via synapses and electrically via gap junctions (see Pereda, 2014).

Also notice in Figure 6.5 that the retina is in a sense inside-out: Light reaches the receptor layer only after passing through the other layers. Then, once the receptors have been activated, the neural message is transmitted back out through the retinal layers to the retinal ganglion cells, whose axons project across the outside of the retina before gathering together in a bundle and exiting the eyeball. This inside-out arrangement creates two visual problems: One is that the incoming light is distorted by the retinal tissue through which it must pass before reaching the receptors. The other is that for the bundle of retinal ganglion cell axons to leave the eye, there must be a gap in the receptor layer; this gap is called the **blind spot**.

The first of these two problems is minimized by the fovea (see Figure 6.6). The **fovea** is an indentation, about 0.33 centimeter in diameter, at the center of the retina;

Figure 6.5 The cellular structure of the mammalian retina.

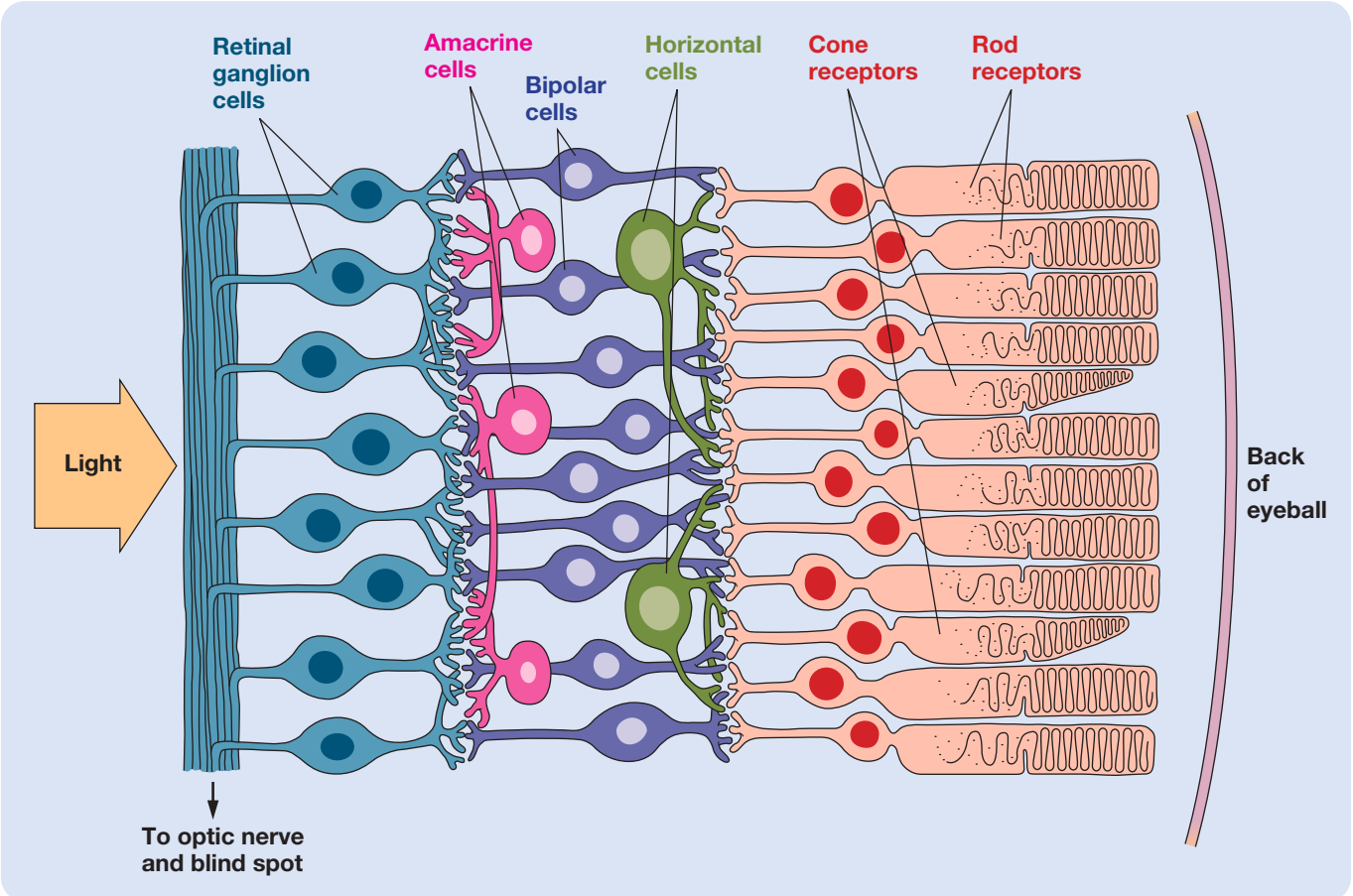
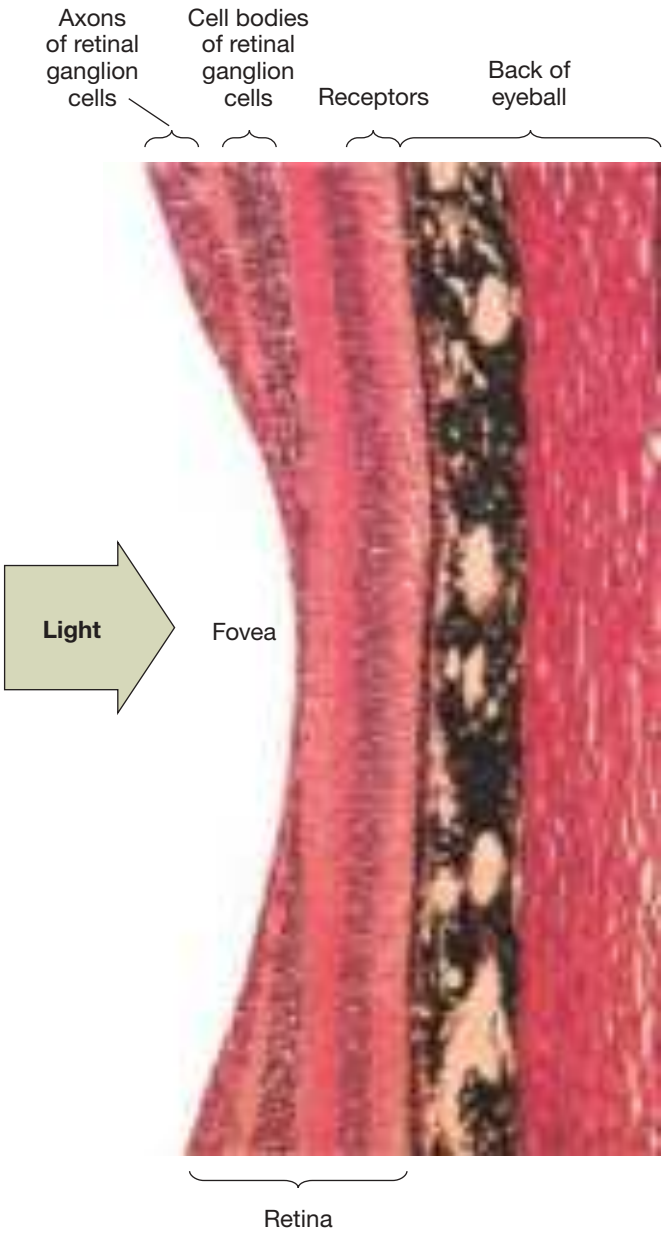


Figure 6.6 A section of the retina. The fovea is the indentation at the center of the retina; it is specialized for high-acuity vision.



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it is the area of the retina that is specialized for high-acuity vision (for seeing fine details). The thinning of the retinal ganglion cell layer at the fovea reduces the distortion of incoming light. The blind spot, the second of the two visual problems created by the inside-out structure of the retina, requires a more creative solution—which is illustrated in the accompanying Check It Out demonstration.

In the Check It Out demonstration, you will experience **completion** (or *filling in*). The visual system uses information provided by the receptors around the blind spot to fill in the gaps in your retinal images. When the visual system detects a straight bar going into one side of the blind spot and another straight bar leaving the other side, it fills in the missing bit for you; and what you see is a continuous straight bar, regardless of what is actually there. The completion phenomenon is one of the most compelling demonstrations that the visual system does much more than make a faithful copy of the external world.

It is a mistake to think that completion is merely a response to blind spots. Indeed, completion plays an important role in normal vision (see Murray & Herrmann, 2013; Weil & Rees, 2011). When you look at an object, your visual system does not conduct an image of that object from your retina to your cortex. Instead, it extracts key information about the object—primarily information about its edges and their location—and conducts that information to the cortex, where a perception of the entire object is created from that partial information. For example, the color and brightness of large unpatterned surfaces are not perceived directly but are filled in (completed) by a completion process called **surface interpolation** (the process by which we perceive surfaces; the visual system extracts information about edges and from it infers the appearance of large surfaces). The central role of surface interpolation in vision is an extremely important but counterintuitive concept. We suggest you read this paragraph again and think about it. Are your creative thinking skills developed enough to feel comfortable with this new way of thinking about your own visual system?

Journal Prompt 6.2

Try to give a specific example of a situation where surface interpolation would occur.

Cone and Rod Vision

LO 6.4 Describe the duplexity theory of vision and explain the differences between the photopic and scotopic systems.

You likely noticed in Figure 6.5 that there are two different types of receptors in the human retina: cone-shaped receptors called **cones** and rod-shaped receptors called **rods** (see Figure 6.7). The existence of these two types of receptors puzzled researchers until 1866, when it was first noticed that species active only in the day tend to have cone-only retinas, and species active only at night tend to have rod-only retinas.

From this observation emerged the **duplexity theory** of vision—the theory that cones and rods mediate different kinds of vision. **Photopic vision** (cone-mediated vision) predominates in good lighting and provides high-acuity (finely detailed) colored perceptions of the world. In dim illumination, there is not enough light to reliably excite the cones, and the more sensitive

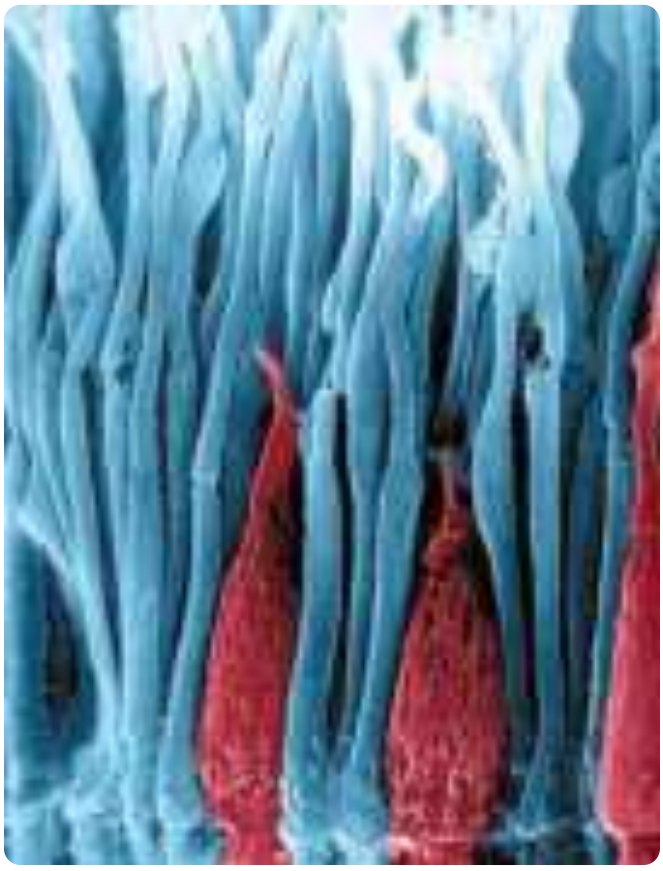
Check It Out

Your Blind Spot and Completion

First, prove to yourself that you do have areas of blindness that correspond to your retinal blind spots. Close your left eye and stare directly at the A below, trying as hard as you can to not shift your gaze. While keeping the gaze of your right eye fixed on the A, hold the text at different distances from you until the black dot to the right of the A becomes focused on your blind spot and disappears at about 13 centimeters (5 inches).

If each eye has a blind spot, why is there not a black hole in your perception of the world when you look at it with one eye? You will discover the answer by focusing on B with your right eye while holding the text at the same distance as before. Suddenly, the broken line to the right of B will become whole. Now focus on C at the same distance with your right eye. What do you see?

Figure 6.7 Cones and rods. The red colored cells are cones; the blue colored cells are rods.



Ralph C. Eagle, Jr./Science Source

scotopic vision (rod-mediated vision) predominates. However, the sensitivity of scotopic vision is not achieved without cost: Scotopic vision lacks both the detail and the color of photopic vision.

The differences between photopic and scotopic vision result in part from a difference in the way the two systems are "wired." As Figure 6.8 illustrates, there is a large difference in convergence between the two systems. In the scotopic system, the output of several hundred rods converges on a single retinal ganglion cell, whereas in the photopic system, only a few cones converge on each retinal ganglion cell. As a result, when dim light stimulates many rods simultaneously, the outputs of this stimulation converge and *summate (*add*)* on the retinal ganglion cell. On the other hand, the effects of the same dim light applied to a sheet of cones cannot summate to the same degree, and the retinal ganglion cells may not respond at all to the light.

The convergent scotopic system pays for its high degree of sensitivity with a low level of acuity. When a retinal ganglion cell that receives input from hundreds of rods changes its firing, the brain has no way of knowing which portion of the rods contributed to the change. Although a more intense light is required to change the firing of a retinal ganglion cell that receives signals from cones, when such a retinal ganglion cell does react, there is less ambiguity about the location of the stimulus that triggered the reaction.

Figure 6.8 Schematic representations of the convergence of cones or rods on a retinal ganglion cell. There is a low degree of convergence in cone-fed pathways and a high degree of convergence in rod-fed pathways.

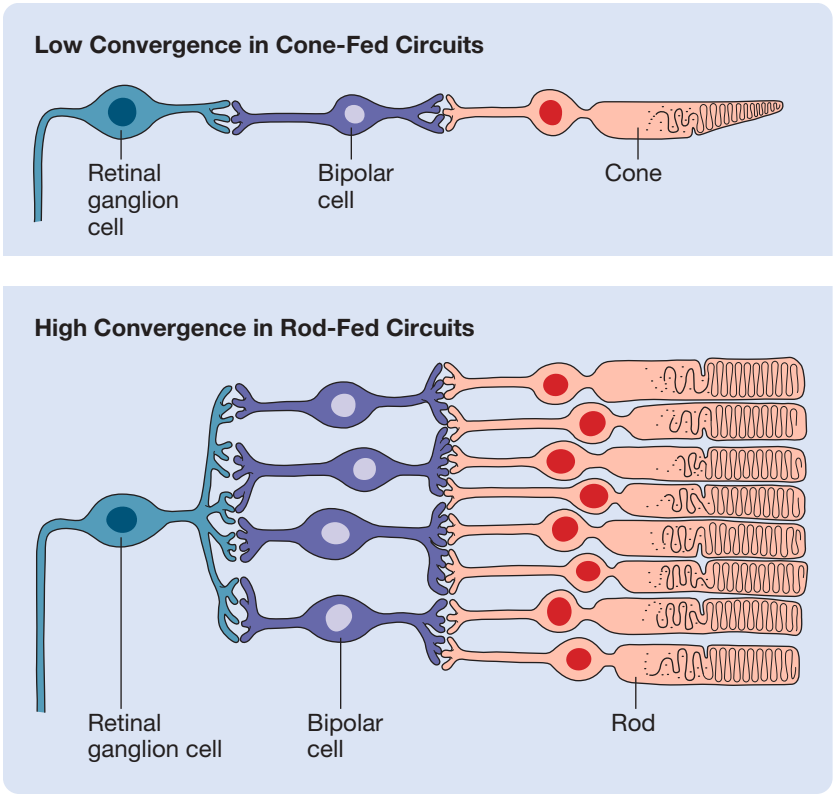
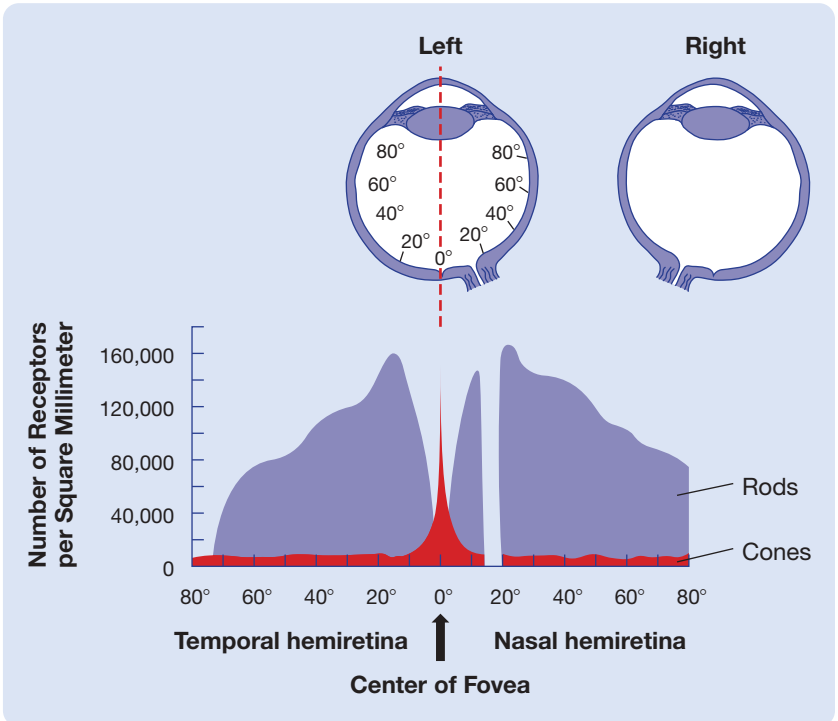


Figure 6.9 The distribution of cones and rods over the human retina. The figure illustrates the number of cones and rods per square millimeter as a function of distance from the center of the fovea.



Based on Lindsay, P. H., & Norman, D. A. (1977). *Human Information Processing* (2nd ed.). New York, NY: Academic Press.

Cones and rods differ in their distribution on the retina. As Figure 6.9 illustrates, there are no rods at all in the fovea, only cones. At the boundaries of the foveal indentation, the proportion of cones declines markedly, and there is an increase in the number of rods. The density of rods reaches a maximum at 20 degrees from the center of the fovea. Notice that there are more rods in the *nasal hemiretina* (the half of each retina next to the nose) than in the *temporal hemiretina* (the half of each retina next to the temples).

Spectral Sensitivity

LO 6.5 **Explain the difference between the photopic and scotopic spectral sensitivity curves and explain how that difference can account for the Purkinje effect.**

Generally speaking, more intense lights appear brighter. However, wavelength also has a substantial effect on the perception of brightness. Because our visual systems are not equally sensitive to all wavelengths in the visible spectrum, lights of the same intensity but of different wavelengths can differ markedly in brightness. A graph of the relative brightness of lights of the same intensity presented at different wavelengths is called a *spectral sensitivity curve*.

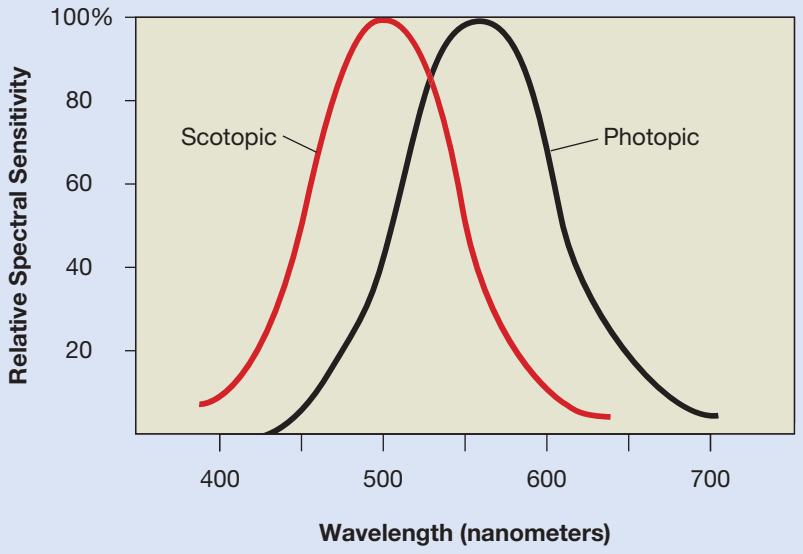
By far the most important thing to remember about spectral sensitivity curves is that humans and other animals with both cones and rods have two of them: a **photopic spectral sensitivity curve** and a **scotopic spectral sensitivity curve**. The photopic spectral sensitivity of humans can be determined by having subjects judge the relative brightness of different wavelengths of light shone on the fovea. Their scotopic spectral sensitivity can be determined by asking subjects to judge the relative brightness of different wavelengths of light shone on the periphery of the retina at an intensity too low to activate the few peripheral cones located there.

The photopic and scotopic spectral sensitivity curves of human subjects are plotted in Figure 6.10. Under photopic conditions, notice that the visual system is maximally sensitive to wavelengths of about 560 nanometers; thus, under photopic conditions, a

light at 500 nanometers would have to be much more intense than one at 560 nanometers to be seen as equally bright. In contrast, under scotopic conditions, the visual system is maximally sensitive to wavelengths of about 500 nanometers; thus, under scotopic conditions, a light of 560 nanometers would have to be much more intense than one at 500 nanometers to be seen as equally bright.

Because of the difference in photopic and scotopic spectral sensitivity, an interesting visual effect can be observed during the transition from photopic to scotopic vision. In 1825, Jan Purkinje described the following occurrence, which has become known as the **Purkinje effect** (pronounced "pur-KIN-jee"). One evening, just before dusk, while Purkinje was walking in his garden, he noticed how his yellow and red flowers appeared brighter in relation to his blue ones. What amazed him was that just a few minutes later, as the sun went down, the relative brightness of his flowers had somehow been reversed; the entire scene, when viewed at night, appeared completely in shades of gray, but most of the blue flowers appeared as brighter shades of gray than the yellow and red ones. Can you explain this shift in relative brightness by referring to the photopic and scotopic spectral sensitivity curves in Figure 6.10?

Figure 6.10 Human photopic (cone) and scotopic (rod) spectral sensitivity curves. The peak of each curve has been arbitrarily set at 100 percent.



Eye Movement

LO 6.6 **Describe the three types of involuntary fixational eye movements and explain what happens when all eye movements are blocked.**

If cones are responsible for mediating high-acuity color vision under photopic conditions, how can they accomplish their task when most of them are crammed into the fovea? (See Figure 6.9.) Look around you. What you see is not a few colored details at the center of a grayish scene. You seem to see an expansive, richly detailed, lavishly colored world. How can such a perception be the product of a photopic system that, for the most part, is restricted to a few degrees in the center of your *visual field* (the entire area that you can see at a particular moment)? The Check It Out demonstration provides a clue. It shows that what we see is determined not just by what is projected on the retina at that instant. Although we are not aware of it, the eyes continually scan the visual field, and our visual perception at any instant is a summation of recent visual information. It is because of this *temporal integration* that the world does not vanish momentarily each time we blink.

Check It Out

Periphery of Your Retina Does Not Mediate the Perception of Detail or Color

Close your left eye, and with your right eye stare at the fixation point (+) at a distance of about 13 centimeters (5 inches) from the page. Be very careful that your gaze does not shift. You will notice when your gaze is totally fixed that it is difficult to see detail and color at 20 degrees or more from the fixation point because there are so few cones there. Now look at the page again with your right eye, but this time without fixing your gaze. Notice the difference that eye movement makes to your vision.

W	F	D	M	E	A	+
50°	40°	30°	20°	10°	5°	0°

Our eyes continuously move even when we try to keep them still (i.e., fixated). Involuntary **fixational eye movements** are of three kinds: tremor, drifts, and **saccades** (small jerky movements, or flicks; pronounced "sah-KAHDS"). Although we are normally unaware of fixational eye movements, they have a critical visual function (see Ibbotson & Krekelberg, 2011; Spering & Carrasco, 2015; Zirnsak & Moore, 2014). When eye movements or their main effect (movement of images on the retina) are blocked, visual objects begin to fade and disappear. This happens because most visual neurons respond only to changing images; if retinal images are artificially stabilized (kept from moving on the retina), the images start to disappear and reappear. Thus, eye movements enable us to see during fixation by keeping the images moving on the retina.

Visual Transduction: The Conversion of Light to Neural Signals

LO 6.7 Describe the process of visual transduction.

Transduction is the conversion of one form of energy to another. *Visual transduction* is the conversion of light to neural signals by the visual receptors. A breakthrough in the study of visual transduction came in 1876 when a red *pigment* (a pigment is any substance that absorbs light) was extracted from rods. This pigment had a curious property. When the pigment—which became known as **rhodopsin**—was exposed to continuous intense light, it was *bleached* (lost its color) and lost its ability to absorb light, but when it was returned to the dark, it regained both its redness and its light-absorbing capacity.

It is now clear that rhodopsin's absorption of light (and the accompanying bleaching) is the first step in rod-mediated vision. Evidence comes from demonstrations that the degree to which rhodopsin absorbs light in various situations predicts how humans see under the very same conditions. For example, it has been shown that the degree to which rhodopsin absorbs lights of different wavelengths is related to the ability of humans and other animals with rods to detect the presence of different wavelengths of light under scotopic conditions. Figure 6.11 illustrates the relationship between the **absorption spectrum** of rhodopsin and the human scotopic spectral sensitivity curve. The fact that the two curves are nearly identical leaves little doubt that, in dim light, our sensitivity to various wavelengths is a direct consequence of rhodopsin's ability to absorb them.

Rhodopsin is a G-protein–coupled receptor that responds to light rather than to neurotransmitter molecules (see Krishnan & Schiöth, 2015; Manglik & Kobilka, 2014). Rhodopsin receptors, like other G-protein–coupled receptors, initiate a cascade of intracellular chemical events when they are activated (see Figure 6.12). When rods are in darkness, their sodium channels are partially open, thus keeping the rods slightly depolarized and allowing a steady flow of excitatory glutamate neurotransmitter molecules to emanate from them. However, when rhodopsin receptors are bleached by light, the resulting cascade of intracellular chemical events closes the sodium channels, hyperpolarizes the rods, and reduces the release of glutamate (see Oesch, Kothmann, & Diamond, 2011). The transduction of light by rods exemplifies an important point: Signals are often transmitted through neural systems by decreases in activity.

Figure 6.11 The absorption spectrum of rhodopsin compared with the human scotopic spectral sensitivity curve.

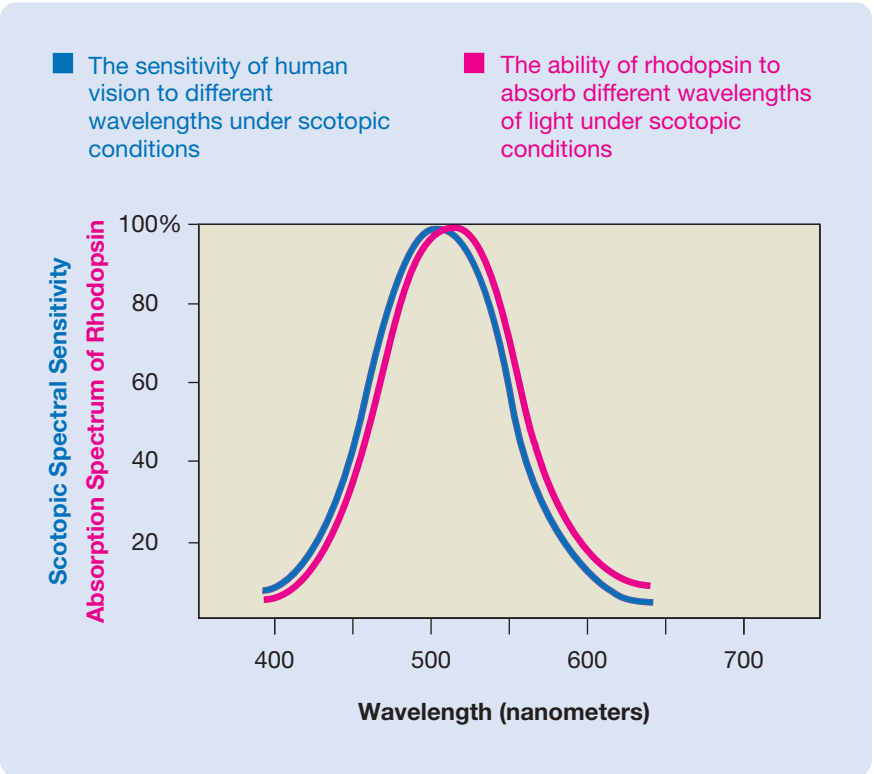
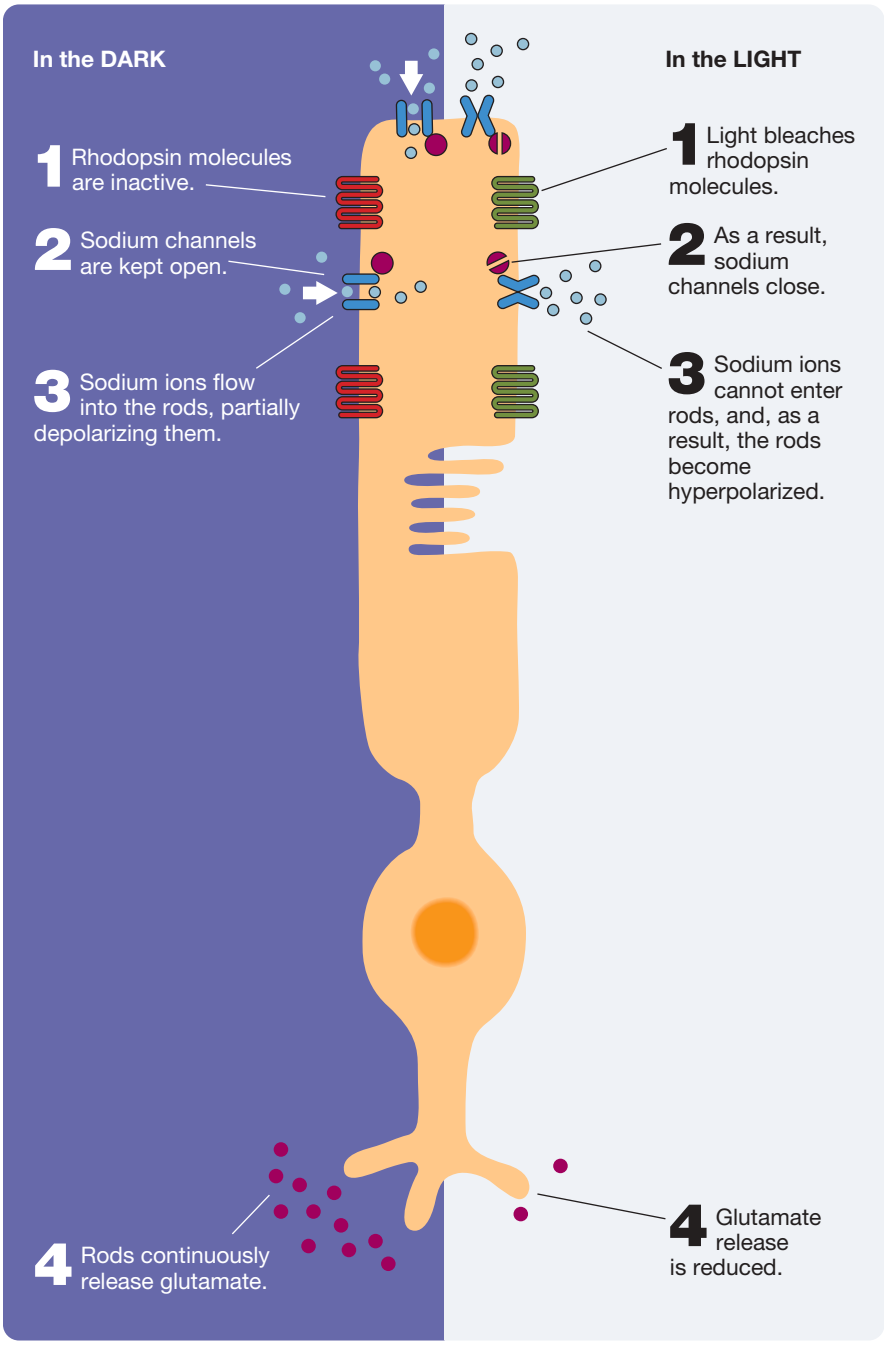


Figure 6.12 The inhibitory response of rods to light. When light bleaches rhodopsin molecules, the rods' sodium channels close; as a result, the rods become hyperpolarized and release less glutamate.



From Retina to Primary Visual Cortex

Many pathways in the brain carry visual information. By far the largest and most thoroughly studied visual pathways are the **retina-geniculate-striate pathways**, which conduct signals from each retina to the **primary visual cortex** (also known as *striate cortex* or *V1*) via the **lateral geniculate nuclei** of the thalamus.

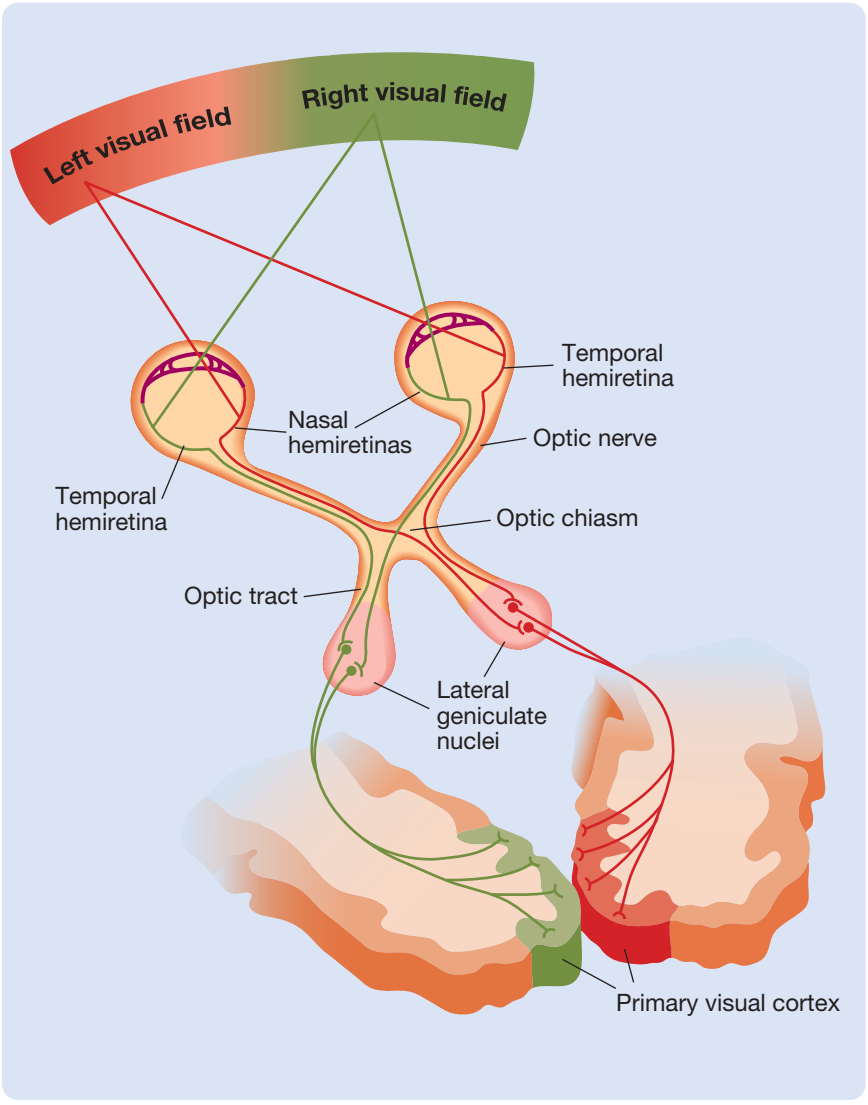
Retina-Geniculate-Striate System

LO 6.8 **Describe the components and layout of the retina-geniculate-striate system.**

About 90 percent of axons of retinal ganglion cells become part of the retina-geniculate-striate pathways (see Tong, 2003). No other sensory system has such a predominant pair (left and right) of pathways to the cortex. The organization of these visual pathways is illustrated in Figure 6.13. Examine it carefully.

The main idea to take away from Figure 6.13 is that all signals from the left visual field reach the right primary visual cortex, either ipsilaterally from the *temporal hemiretina* of the right eye or contralaterally (via the *optic chiasm*) from the *nasal hemiretina* of the left eye—and that the opposite is true of all signals from the right visual field. Each lateral geniculate nucleus has six layers, and each layer receives input from all parts of the contralateral visual field of one eye. In other words, each lateral geniculate nucleus receives visual input only from the contralateral visual field; three layers receive input from one eye, and three receive input from the other. Most of the lateral geniculate neurons that project to the primary visual cortex terminate in the lower part of cortical layer IV (see Muckli & Petro, 2013), producing a characteristic stripe, or striation, when viewed in cross section—hence, primary visual cortex is often referred to as *striate cortex*. Note: Figure 6.13 depicts only the axonal projections from the lateral geniculate nuclei to the primary visual cortex, but there are just as many projections from the primary visual cortex to the lateral geniculate nuclei.

Figure 6.13 The retina-geniculate-striate system: the neural projections from the retinas through the lateral geniculate nuclei to the left and right primary visual cortex (striate cortex). The colors indicate the flow of information from various parts of the visual fields of each eye to various parts of the visual system.



Based on Netter, F. H. (1962). *The CIBA Collection of Medical Illustrations. Vol. 1, The Nervous System.* New York, NY: CIBA.

Retinotopic Organization

LO 6.9 **In the context of the retina-geniculate-striate system, explain what is meant by retinotopic.**

The retina-geniculate-striate system is **retinotopic**; each level of the system is organized like a map of the retina. This means two stimuli presented to adjacent areas of the retina excite adjacent neurons at all levels of the system (see Kremkow et al., 2016). The retinotopic layout of the primary visual cortex has a disproportionately large representation of the fovea; although the fovea is only a small part of the retina, a relatively large proportion of the primary visual cortex (about 25 percent) is dedicated to the analysis of its input.

A dramatic demonstration of the retinotopic organization of the primary visual cortex was provided by Dobelle, Mladejovsky, and Girvin (1974). They implanted an array of electrodes in the primary visual cortex of patients who were blind because of damage to their eyes. If electrical current was administered simultaneously through an array of electrodes forming a shape, such as a cross, on the surface of a patient's cortex, the patient reported "seeing" a glowing image of that shape. This finding and recent research on retinal implants (see Roska & Sahel, 2018; Wood, 2018) could be the basis for the development of visual prostheses that could benefit many blind people (see Shepherd et al., 2013).

Journal Prompt 6.3

How does the prosthesis developed by Dobelle et al. (1974) demonstrate the retinotopic organization of the primary visual cortex?

The M and P Channels

LO 6.10 **Describe the M and P channels.**

Not apparent in Figure 6.13 is the fact that at least two parallel channels of communication flow through each lateral geniculate nucleus. One channel runs through the top four layers. These layers are called the **parvocellular layers** (or *P layers*) because they are composed of neurons with small cell bodies (*parvo* means "small"). The other channel runs through the bottom two layers, which are called the **magnocellular layers** (or *M layers*) because they are composed of neurons with large cell bodies (*magno* means "large").

The parvocellular neurons are particularly responsive to color, fine pattern details, and stationary or slowly moving objects. In contrast, the magnocellular neurons are particularly responsive to movement. Cones provide the majority of the input to the P layers, whereas rods provide the majority of the input to the M layers.

The parvocellular and magnocellular neurons project to different areas in the lower part of layer IV of the striate cortex. In turn, these M and P areas of lower layer IV project to different areas of visual cortex.

Scan Your Brain

This is a good place to pause and scan your brain to check your knowledge on the basics of the visual process before you move on to studying how we perceive edges and color. Fill in the following blanks with the most appropriate terms. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. Light reflected from objects enters the eye though the _____.
2. Depending on how close or far away an object is, the lens is adjusted using the _____ muscles.
3. About 25 percent of the primary visual cortex is dedicated to analyzing input from the _____.
4. _____ is the process by which the lenses adjust their shape to bring images to focus on the retina.
5. The difference in the position of the same image on the two retinas is called _____.
6. Nasal hemiretina of the right visual field project to the _____ hemisphere, while temporal hemiretina project to the _____ hemisphere.
7. The location on the retina where a bundle of cell axons leaves the eye is called the _____.
8. The theory that the two types of retinal receptors, rods and cones, mediate different kinds of vision is called the _____ theory.
9. There are two _____ channels that run through the lateral geniculate nucleus called M and P channels.

Scan Your Brain answers: (1) pupil, (2) ciliary, (3) fovea, (4) Accommodation, (5) binocular disparity, (6) ipsilateral, contralateral, (7) blind spot, (8) duplexity, (9) parallel.

Seeing Edges

Edge perception (seeing edges) does not sound like a particularly important topic, but it is. Edges are the most informative features of any visual display because they define the extent and position of the various objects in it. Given the importance of perceiving visual edges and the unrelenting pressure of natural selection, it is not surprising that the visual systems of many species are particularly good at edge perception.

Before considering the visual mechanisms underlying edge perception, it is important to appreciate exactly what a visual edge is. In a sense, a visual edge is nothing: It is merely the place where two different areas of a visual image meet. Accordingly, the perception of an edge is really the perception of a contrast between two adjacent areas of the visual field. This module reviews the perception of edges (the perception of contrast) between areas that differ from one another in brightness (i.e., that show brightness contrast).

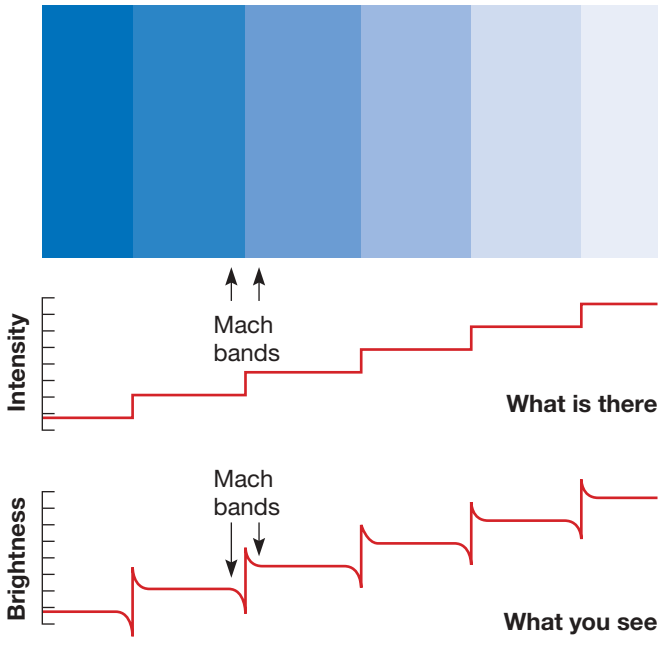
Contrast Enhancement

LO 6.11 Describe contrast enhancement.

Carefully examine the stripes in Figure 6.14. The intensity graph in the figure indicates what is there—a series of homogeneous stripes of different intensity. But this is not exactly what you see, is it? What you see is indicated in the brightness graph. Adjacent to each edge, the brighter stripe looks brighter than it really is and the darker stripe looks darker than it really is. The nonexistent stripes of brightness and darkness running adjacent to the edges are called *Mach bands*; they enhance the contrast at each edge and make the edge easier to see.

It is important to appreciate that **contrast enhancement** is not something that occurs just in books. Although we are normally unaware of it, every edge we look at is highlighted for us by the contrast-enhancing mechanisms of our nervous systems. In effect, our perception of edges is better than the real thing (as determined by measurements of the physical properties of the light entering our eyes).

Figure 6.14 The illusory bands visible in this figure are often called Mach bands, although Mach used a different figure to generate them in his studies (see Eagleman, 2001).



Receptive Fields of Visual Neurons: Hubel & Wiesel

LO 6.12 Define the term *receptive field* and describe the methods used by David Hubel and Torsten Wiesel to map the receptive fields of visual system neurons.

The Nobel Prize–winning research of David Hubel and Torsten Wiesel (see Hubel & Wiesel, 2004) is the fitting focus of this discussion of seeing edges. Their research revealed much about the neural mechanisms of vision, and their method has been adopted by subsequent generations of sensory neurophysiologists.

Hubel and Wiesel's influential method is a technique for studying single neurons in the visual systems of laboratory animals—their research subjects were cats and monkeys. First, the tip of a microelectrode is positioned near a single neuron in the part of the visual system under investigation. During testing, eye movements are blocked by paralyzing the eye muscles, and the images on a screen in front of the subject are focused sharply on the retina by an adjustable lens. The next step in the procedure is to identify the receptive field of the neuron. The **receptive field** of a visual neuron is the area of the visual field within which it is possible for a visual stimulus to influence the firing of that neuron. The final step in the method is to record the responses of the neuron to various simple stimuli within its receptive field in order to characterize the types of stimuli that most influence its activity. Then the electrode is advanced slightly, and the entire process of identifying and characterizing the receptive field properties is repeated for another neuron, and then for another, and another, and so on. The general strategy is to begin by studying neurons near the receptors and gradually work up through "higher" and "higher" levels of the system in an effort to understand the increasing complexity of the neural responses at each level.

Receptive Fields of the Retina-Geniculate-Striate System: Hubel & Wiesel

LO 6.13 Describe the work of Hubel & Wiesel that helped to characterize the receptive fields of retinal ganglion cells, lateral geniculate neurons, and striate neurons of lower layer IV.

Hubel and Wiesel (1979) began their studies of visual system neurons by recording from the three levels of the retina-geniculate-striate system: first from retinal ganglion cells, then from lateral geniculate neurons, and finally from the striate neurons of lower layer IV. They tested the neurons with stationary spots of *achromatic* (uncolored) light shone on the retina. They found little change in the receptive fields as they worked through the levels.

When Hubel and Wiesel compared the receptive fields recorded from retinal ganglion cells, lateral geniculate nuclei, and lower layer IV striate neurons, four commonalties were readily apparent:

- At each level, the receptive fields in the foveal area of the retina were smaller than those at the periphery; this is consistent with the fact that the fovea mediates fine-grained (high-acuity) vision.
- All the neurons (retinal ganglion cells, lateral geniculate neurons, and lower layer IV neurons) had receptive fields that were circular.
- All the neurons were **monocular**; that is, each neuron had a receptive field in one eye but not the other.
- Many neurons at each of the three levels of the retina-geniculate-striate system had receptive fields that comprised an excitatory area and an inhibitory area separated by a circular boundary.

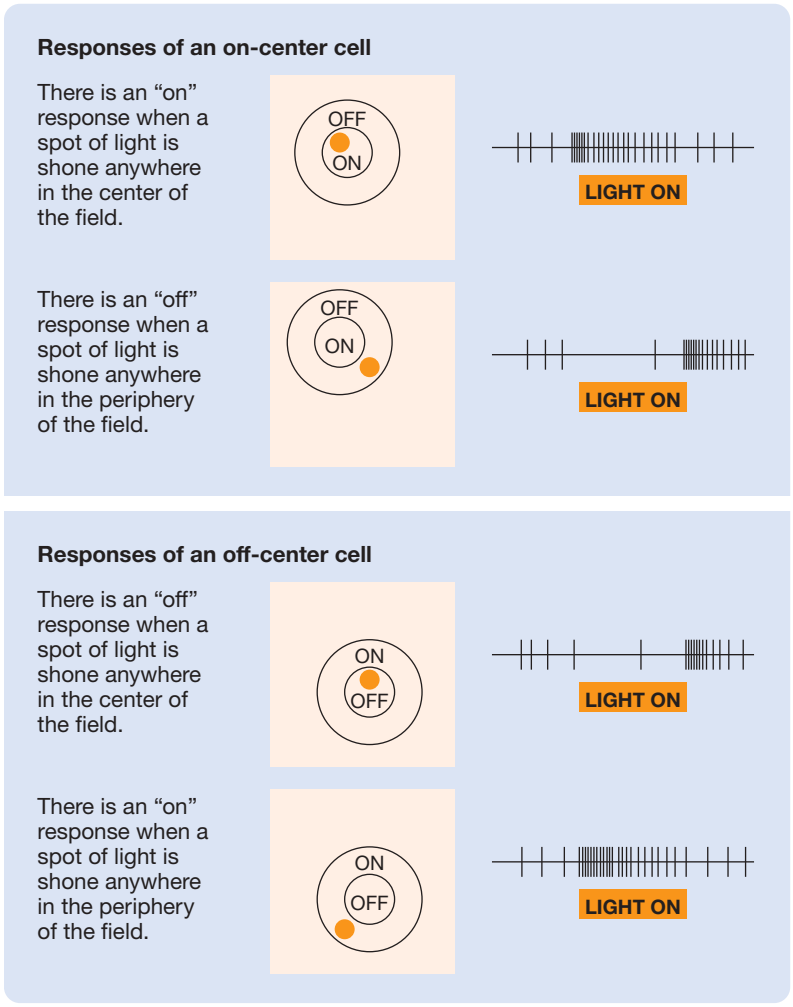
Let us explain this last point—it is important. When Hubel and Wiesel shone a spot of achromatic light onto the various parts of the receptive fields of a neuron in the retina-geniculate-striate pathway, they discovered two different responses. The neuron responded with either "on" firing or "off" firing, depending on the location of the spot of light in the receptive field. That is, the neuron either displayed a burst of firing when the light was turned on (*"on" firing*), or it displayed an inhibition of firing when the light was turned on and a burst of firing when it was turned off (*"off" firing*).

For most of the retinal ganglion cells, lateral geniculate nuclei, and lower layer IV striate neurons, the reaction—"on" firing or "off" firing—to a light in a particular part of the receptive field was quite predictable. It depended on whether they were on-center cells or off-center cells, as illustrated in Figure 6.15.

On-center cells respond to lights shone in the central region of their receptive fields with "on" firing and to lights shone in the periphery of their receptive fields with inhibition, followed by "off" firing when the light is turned off. **Off-center cells** display the opposite pattern: They respond with inhibition and "off" firing in response to lights in the center of their receptive fields and with "on" firing to lights in the periphery of their receptive fields.

In effect, on-center and off-center cells respond best to contrast. Figure 6.16 illustrates this point. The most effective way to influence the firing rate of an on-center or off-center cell is to maximize the contrast between the center and the periphery of its receptive field by illuminating either the entire center or the entire surround (periphery) while leaving the other region completely dark. Diffusely illuminating the entire receptive field has little effect on firing. Hubel and Wiesel thus concluded that one function of many of the neurons in the retina-geniculate-striate system is to respond to the degree of brightness contrast between

Figure 6.15 The receptive fields of an on-center cell and an off-center cell.



the two areas of their receptive fields (see Livingstone & Hubel, 1988).

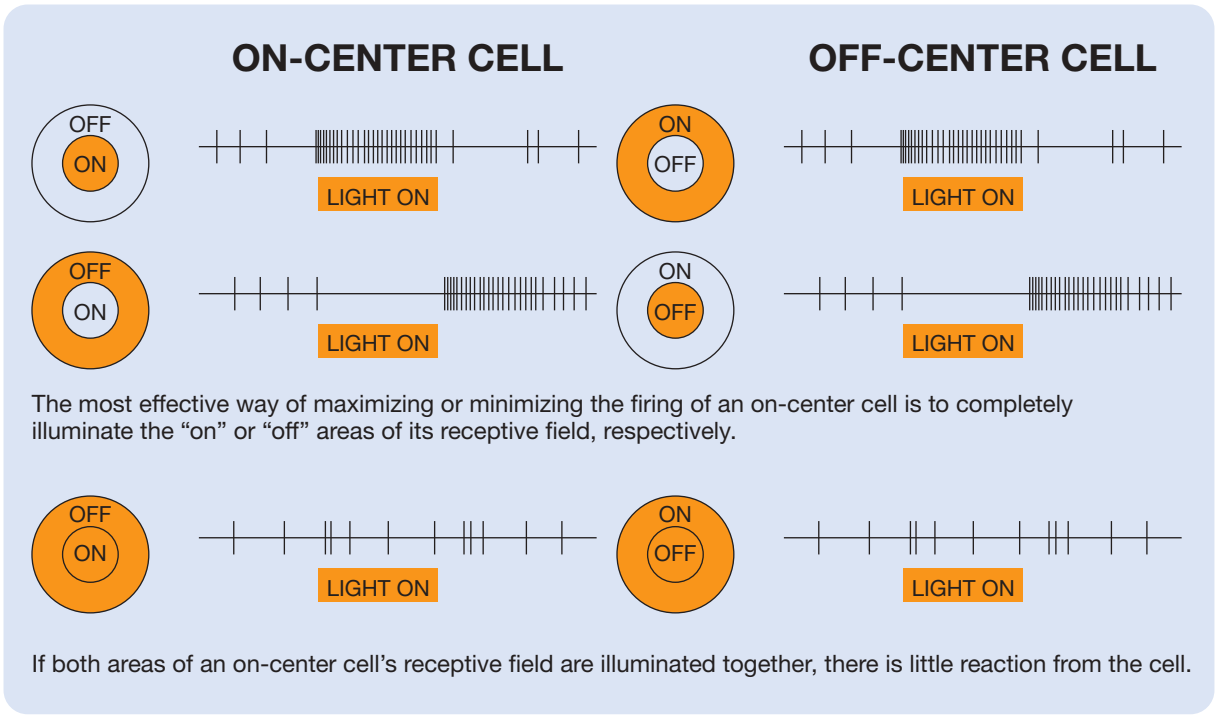
Before moving on, notice one important thing from Figures 6.15 and 6.16 about visual system neurons: Most are continually active, even when there is no visual input (see Lee et al., 2013). Indeed, spontaneous activity is characteristic of most cerebral neurons, and responses to external stimuli consume only a small portion of the energy required for ongoing brain activity (see Zhang & Raichle, 2010).

Receptive Fields of Primary Visual Cortex Neurons: Hubel & Wiesel

LO 6.14 Describe the work of Hubel & Wiesel that characterized the receptive fields of simple and complex cells in the primary visual cortex.

The striate cortex neurons you just read about—that is, the neurons of lower layer IV—have receptive fields unlike those of the vast majority of striate neurons. The receptive fields of most primary visual cortex neurons fall into one of two classes: simple or complex. Neither of these classes includes the neurons of lower layer IV.

Figure 6.16 The responses of an on-center cell to contrast.



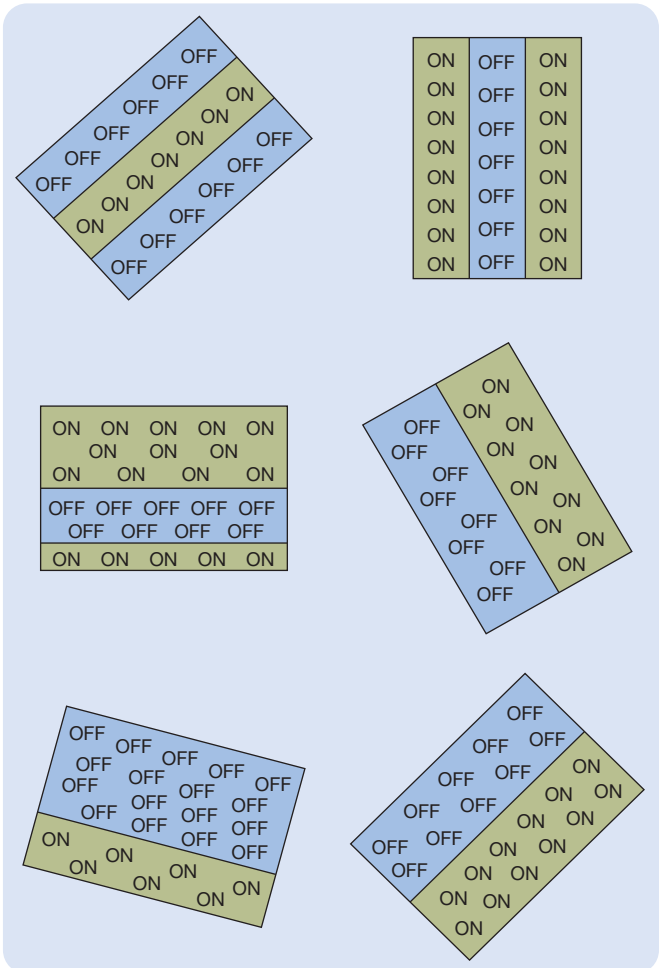
SIMPLE STRIATE CELLS. **Simple cells**, like lower layer IV neurons, have receptive fields that can be divided into antagonistic "on" and "off" regions and are thus unresponsive to diffuse light. And like lower layer IV neurons, they are all monocular. The main difference is that the borders between the "on" and "off" regions of the cortical receptive fields of simple cells are straight lines rather than circles. Several examples of receptive fields of simple cortical cells are presented in Figure 6.17. Notice that simple cells respond best to bars of light in a dark field, dark bars in a light field, or single straight edges between dark and light areas; that each simple cell responds maximally only when its preferred straight-edge stimulus is in a particular position and in a particular orientation (see Vidyasagar & Eysel, 2015); and that the receptive fields of simple cortical cells are rectangular rather than circular.

COMPLEX STRIATE CELLS. **Complex cells** are more numerous than simple cells. Like simple cells, complex cells have rectangular receptive fields, respond best to straight-line stimuli in a specific orientation, and are unresponsive to diffuse light. However, complex cells differ from simple cells in three important ways. First, they have larger receptive fields. Second, it is not possible to divide the receptive fields of complex cells into static "on" and "off" regions: A complex cell responds to a particular straight-edge stimulus of a particular orientation regardless of its position within the receptive field of that cell. Thus, if a stimulus (e.g., a 45-degree bar of light) that produces "on" firing in a particular complex cell is swept across that cell's receptive field, the cell will respond continuously to it as it moves across the field. Many complex cells respond more robustly to the movement of a straight line across their receptive fields in a particular direction. Third, unlike simple cortical cells, which are all monocular (respond to stimulation of only one of the eyes), many complex cells are **binocular** (respond to stimulation of either eye). Indeed, in monkeys, more than half the complex cortical cells are binocular.

BINOCULAR COMPLEX STRIATE CELLS. If the receptive field of a binocular complex cell is measured through one eye and then through the other, the receptive fields in each eye turn out to have almost exactly the same position in the visual field as well as the same orientation preference. In other words, what you learn about the cell by stimulating one eye is confirmed by stimulating the other. What is more, if the appropriate stimulation is applied through both eyes simultaneously, a binocular cell usually fires more robustly than if only one eye is stimulated.

Most of the binocular cells in the primary visual cortex of monkeys display some degree of *ocular dominance*; that is, they respond more robustly to stimulation of one eye than they do to the same stimulation of the other. In addition, some binocular cells fire best when the preferred stimulus is presented to both eyes at the same time but in slightly different positions on the two retinas (e.g., Ohzawa, 1998). In other words, these cells respond best to *retinal disparity* and thus are likely to play a role in depth perception (e.g., Livingstone & Tsao, 1999).

Figure 6.17 Examples of receptive fields of simple striate cells.



Organization of Primary Visual Cortex: Hubel & Wiesel's Findings

LO 6.15 **Describe the organization of the primary visual cortex.**

After describing the receptive fields of visual cortex neurons, Hubel and Wiesel focused their analyses on how neurons with different receptive fields are organized in the primary visual cortex. They reached three important conclusions about the organization of primate visual cortex:

- They concluded that the primary visual cortex was organized into functional *vertical* (in this context, *vertical* means at right angles to the cortical layers) columns: All of the neurons in the same vertical column

respond to stimuli applied to the same area of the retina, are dominated by the same eye (if they display dominance or monocularity), and "prefer" the same straight-line angles (if they display a preference for straight-line stimuli).

- They found that the location of various functional columns in primary visual cortex is influenced by the location on the retina of the column's visual fields, by the dominant eye of the column, and by the column's preferred straight-line angle. Hubel and Wiesel concluded that all of the functional columns in the primary visual cortex that analyze input from one area of the retina are clustered together, that half of a cluster receives input from the left eye and the other half receives input from the right eye, and that each cluster includes neurons with preferences for straight-line stimuli of various orientations.
- As Hubel and Wiesel's studies progressed from retina, to thalamus, to lower layer IV of visual cortex, to simple cortical cells, to complex cortical cells, the "preferences" of the neurons became more complex. Hubel and Wiesel concluded that this occurred because neurons with simpler preferences converged on neurons with more complex preferences.

Now that you know a bit about how the visual cortex is organized, you are in a better position to think constructively about Mrs. Richards's fortification illusions.

The Case of Mrs. Richards, Revisited

There was obviously a disturbance in Mrs. Richards's visual system. But where? And what kind of disturbance? And why the straight lines? A simple test located the disturbance. Mrs. Richards was asked to shut one eye and then the other and to report what happened to her illusion when she changed eyes. The answer was "Nothing." This suggested that the disturbance was cortical because the visual cortex is the first part of the retina-geniculate-striate system that contains neurons that receive input from both eyes.

This hypothesis was confirmed by a few simple calculations: The gradual acceleration of the illusion as it spread out to the periphery is consistent with a wave of disturbance expanding from the "foveal area" of the primary visual cortex to its boundaries at a constant rate of about 3 millimeters per minute—the illusion accelerated because proportionally less visual cortex is dedicated to receiving signals from the periphery of the visual field.

And why the lines? Would you expect anything else from an area of the cortex whose elements appear to have a preference for straight-line stimuli?

Changing Concept of the Characteristics of Visual Receptive Fields

LO 6.16 Describe how views about the receptive fields of retinal ganglion cells and lateral geniculate neurons have recently changed.

Since the seminal work of Hubel and Wiesel, there has been a massive amount of research focused on further characterizing the receptive fields of cells in the retina-geniculate-striate system. In general, these studies have discovered that receptive fields are much more complex than was originally recognized.

In this section, we will explain some of the important new findings about the receptive fields of retinal ganglion cells and lateral geniculate neurons—cells that were once believed to have just on-center and off-center receptive fields. As you will see, the characteristics described by Hubel and Wiesel, and others, turned out to be much simpler than what is currently known to be the case.

RETINAL GANGLION CELLS. Recent analyses of the visual processing of stimuli in primates and mice have shown that they have about 20 and 40 distinct sorts of retinal ganglion cells, respectively—each with its own sort of receptive field. In addition to the on-center and off-center receptive fields documented by Hubel and Wiesel, there are also retinal ganglion cells with receptive fields that are selective to one or more of the following: (1) uniform illumination, (2) orientation, (3) motion, and (4) direction of motion (see Baden et al., 2016; Ding et al., 2016; Hillier et al., 2017; Mauss et al., 2017; Morrie & Feller, 2016).

LATERAL GENICULATE CELLS. There has also been recent attention to the functional roles of lateral geniculate cells. Analyses have shown that some cells in the lateral geniculate nucleus have receptive fields that are sensitive to more than just contrast (i.e., on-center and off-center receptive fields). Indeed, those cells have receptive fields that are sensitive to one or more of the following: (1) orientation, (2) motion, and (3) direction of motion (see Sun, Tan, & Ji, 2016). As you may have recognized already, these receptive fields are similar to those of retinal ganglion cells (see Ghodrati, Khaligh-Razavi, & Lehky, 2017).

Changing Concept of Visual Receptive Fields: Contextual Influences in Visual Processing

LO 6.17 Describe the changing view of visual system receptive fields.

Most investigations of the responsiveness of visual system neurons have been based on two implicit assumptions. The first is that the mechanisms of visual processing can be best

identified by studies using simplified, controllable, artificial stimuli (see Einhäuser & König, 2010). The second is that the receptive field properties of each neuron are static, unchanging properties of that neuron. Research that has employed video clips of real scenes involving natural movement suggests that neither of these assumptions is correct (see Haslinger et al., 2012) at any of the three levels of the retina-geniculate-striate system (see Rivlin-Etzion, Grimes, & Rieke, 2018; Rose & Bonhoeffer, 2018).

Studies of the responses of visual cortex to natural scenes—just the type of scenes the visual system has evolved to perceive—indicate that the response of a visual cortex neuron depends not only on the stimuli in its receptive field but also on the larger scene in which these stimuli are embedded (see Baden, Euler, & Berens, 2020; Coen-Cagli, Kohn, & Schwartz, 2015; Dumoulin & Knapen, 2018; Iacaruso, Gasler, & Hofer, 2017). The influences on a visual neuron's activity that are caused by stimuli outside the neuron's receptive field are generally referred to as *contextual influences* (see Gilbert & Li, 2013). Contextual influences can take many forms depending on the exact timing, location, and shape of the visual stimuli under investigation and on the ambient light levels (e.g., Iacaruso, Gasler, & Hofer, 2017; Roth et al., 2016; Tikidji-Hamburyan et al., 2015); and the nature of such contextual influences is dependent on prior exposure to them (see Khan et al., 2018; Thompson et al., 2017). Moreover, contextual signals associated with particular actions or states—such as engaging in locomotion or being exposed to stimuli that have biological relevance (e.g., a stimulus that has previously been associated with the presentation of food)—can help shape the properties of a receptive field (see Fiser et al., 2016; Hrvatin et al., 2018; Khan & Hofer, 2018).

Think for a moment about the implications that the discovery of contextual influences has for understanding how visual receptive fields function. A visual neuron's receptive field was initially assumed to be a property of the neuron resulting from the hardwired convergence of neural circuits; now, a neuron's receptive field is viewed as a plastic property of the neuron that is continually fine-tuned on the basis of prior experience and current signals from the animal's environment.

Journal Prompt 6.4

Why should natural scenes be used to study visual system neurons?

Seeing Color

Color is one of the most obvious qualities of human visual experience. So far in this chapter, we have largely limited our discussion of vision to black, white, and gray. Black is experienced when there is an absence of light; the perception of white is produced by an intense mixture of a wide range of wavelengths in roughly equal proportions; and the perception of gray is produced by the same mixture at lower intensities. In this module, we deal with the perception of colors such as blue, green, and yellow. The correct term for colors is *hues*, but in everyday language they are referred to as colors; and for the sake of simplicity, we will do the same.

What is there about a visual stimulus that determines the color we perceive? To a large degree, the perception of an object's color depends on the wavelengths of light that it reflects into the eye. Figure 6.2 is an illustration of the colors associated with individual wavelengths; however, outside the laboratory, one never encounters objects that reflect single wavelengths. Sunlight and most sources of artificial light contain complex mixtures of most visible wavelengths. Most objects absorb the different wavelengths of light that strike them to varying degrees and reflect the rest. The mixture of wavelengths that objects reflect influences our perception of their color, but it is not the entire story—as you are about to learn.

Component and Opponent Processing

LO 6.18 Describe the component and opponent-process theories of color vision.

The **component theory** (*trichromatic theory*) of color vision was proposed by Thomas Young in 1802 and refined by Hermann von Helmholtz in 1852. According to this theory, there are three different kinds of color receptors (cones), each with a different spectral sensitivity, and the color of a particular stimulus is presumed to be encoded by the ratio of activity in the three kinds of receptors. Young and Helmholtz derived their theory from the observation that any color of the visible spectrum can be matched by a mixing together of three different wavelengths of light in different proportions. This can be accomplished with any three wavelengths, provided that the color of any one of them cannot be matched by a mixing of the other two. The fact that three is normally the minimum number of different wavelengths necessary to match every color suggested that there were three types of receptors.

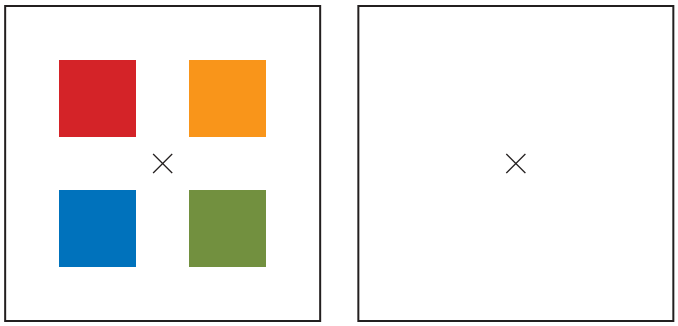
Another theory of color vision, the **opponent-process theory** of color vision, was proposed by Ewald Hering in 1878. He suggested that there are two different classes of cells in the visual system for encoding color and another class for encoding brightness. Hering hypothesized that each of the three classes of cells encoded two complementary color perceptions. One class of color-coding cells signaled red by changing its activity in one direction (e.g., hyperpolarization) and signaled red's complementary color, green, by changing its activity in the other direction (e.g., depolarization). Another class of color-coding cells was hypothesized to signal blue and its complement, yellow, in the same opponent fashion; and a class of brightness-coding cells was hypothesized to similarly signal both black and white. **Complementary colors** are pairs of colors (e.g., green light and red light) that produce white or gray when combined in equal measure.

Hering based his opponent-process theory of color vision on several behavioral observations. One was that complementary colors cannot exist together: There is no such thing as bluish yellow or reddish green (see Billock & Tsou, 2010). Another was that the afterimage produced by staring at red is green and vice versa, and the afterimage produced by staring at yellow is blue and vice versa (try the Check It Out demonstration).

Check It Out

Complementary Afterimages

Have you ever noticed complementary afterimages? To see them, stare at the fixation point (x) in the left panel for 1 minute without moving your eyes, then quickly shift your gaze to the fixation point in the right panel. In the right panel, you will see four squares whose colors are complementary to those in the left panel.



A somewhat misguided debate raged for many years between supporters of the component and opponent theories of color vision. We say "misguided" because it was fueled more by the adversarial predisposition of scientists than by the incompatibility of the two theories. In fact, research subsequently proved that both color-coding mechanisms coexist in our visual systems (see DeValois et al., 2000).

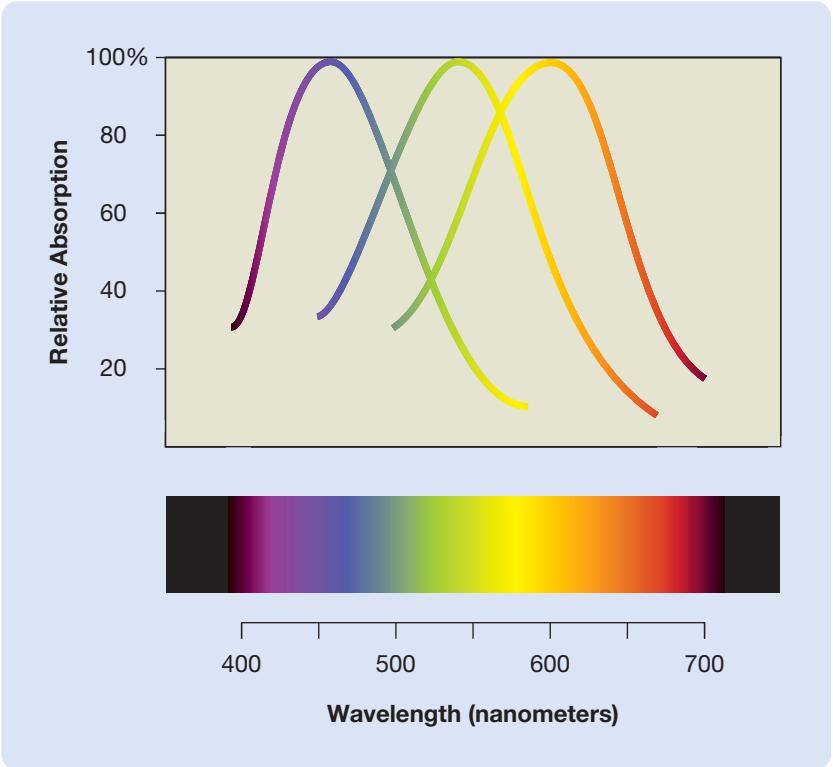
It was the development in the early 1960s of a technique for measuring the absorption spectrum of the photopigment contained in a single cone that allowed researchers (e.g., Wald, 1964) to confirm the conclusion that Young had reached more than a century and a half before. They found that there are indeed three different kinds of cones in the retinas of those vertebrates with good color vision, and they found that each of the three has a different photopigment with its own characteristic absorption spectrum. As Figure 6.18 illustrates, some cones are most sensitive to short wavelengths, some are most sensitive to medium wavelengths, and some are most sensitive to long wavelengths (see Shevell & Kingdom, 2008), but all three respond to most of the wavelengths of the visible spectrum.

Although the coding of color by cones seems to operate on a purely component basis (see Jameson, Highnote, & Wasserman, 2001), there is evidence of opponent processing of color at all subsequent levels of the retina-geniculate-striate system. That is, at all subsequent levels, there are cells that respond in one direction (e.g., increased firing) to one color and in the opposite direction (e.g., decreased firing) to its complementary color (see Joesch & Meister, 2016).

Most primates are *trichromats* (possessing three color vision photopigments). Most other mammals are *dichromats* (possessing two color vision photopigments)—they lack the photopigment sensitive to long wavelengths and thus have difficulty seeing light at the red end of the visible spectrum (see Figure 6.2). In contrast, some birds, fish, and reptiles have four photopigments, and some insects have five or more photopigments—the dragonfly wins first place with ten (see Kelber, 2016).

In a remarkable study, Jacobs and colleagues (2007) inserted into mice a gene for a third photopigment, thus converting them from dichromats to trichromats. Behavioral tests indicated that the transgenic mice had acquired the ability to see additional wavelengths of light.

Figure 6.18 The absorption spectra of the three classes of cones.



Color Constancy and the Retinex Theory

LO 6.19 Describe Land's demonstration of color constancy and explain his retinex theory.

Neither component nor opponent processing can account for the single most important characteristic of color vision: color constancy. **Color constancy** refers to the fact that the perceived color of an object is not a simple function of the wavelengths reflected by it.

Color constancy is an important—but much misunderstood—concept. Let us explain it with an example. As I (SB) write this at 6:15 on a January morning, it is dark outside, and I am working in my office by the light of a tiny incandescent desk lamp. Later in the morning, when students start to arrive, I will turn on my nasty fluorescent office lights; and then, in the afternoon, when the sun is brighter on my side of the building, I will turn off the lights and work by natural light. The point is that because these light sources differ markedly in the wavelengths they emit, the wavelengths reflected by various objects in my office—my blue shirt, for example—change substantially during the course of the day. However, although the wavelengths reflected by my shirt change markedly, its color does not—my shirt will be just as blue in midmorning and in late afternoon as it is now. Color constancy is the tendency for an object to stay the same color despite major changes in the wavelengths of light that it reflects.

Although the phenomenon of color constancy is counterintuitive, its advantage is obvious. Color constancy improves our ability to tell objects apart in a memorable way so that we can respond appropriately to them; our ability to recognize objects would be greatly lessened if their color changed every time there was a change in illumination (see Foster, 2011). In essence, if it were not for color constancy, color vision would have little survival value.

Journal Prompt 6.5

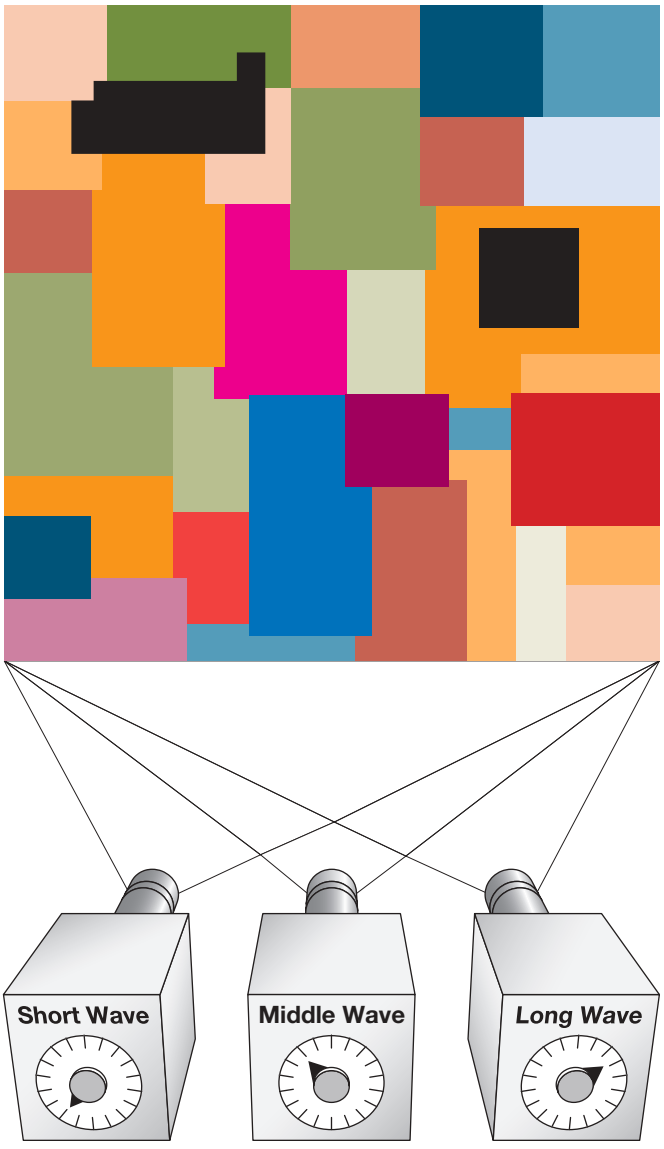
Describe a specific example where color constancy would be adaptive.

Although color constancy is an important feature of our vision, we are normally unaware of it. Under everyday conditions, we have no way of appreciating just how much the wavelengths reflected by an object can change without the object changing its color. It is only in the controlled environment of the laboratory that one can fully appreciate that color constancy is more than an important factor in color vision: It is the essence of color vision.

Edwin Land (1977) developed several dramatic laboratory demonstrations of color constancy. In these demonstrations, Land used three adjustable projectors. Each projector emitted only one wavelength of light: one a short-wavelength light, one a medium-wavelength light, and one a long-wavelength light. Thus, it was clear that only three wavelengths of light were involved in the demonstrations. Land shone the three projectors on a test display like the one in Figure 6.19. (These displays are called *Mondrians* because they resemble the paintings of the Dutch artist Piet Mondrian.)

Land found that adjusting the amount of light emitted from each projector—and thus, the amount of light of each wavelength being reflected by the Mondrian—had no effect at all on the perception of its colors. For example, in one demonstration Land used a photometer to measure the amounts of the three wavelengths reflected by a rectangle judged to be pure blue by his participants. He then adjusted the emittance of the projectors, and he

Figure 6.19 The method of Land's (1977) color-vision experiments. Participants viewed Mondrians illuminated by various proportions of three different wavelengths: a short wavelength, a middle wavelength, and a long wavelength.



measured the wavelengths reflected by a red rectangle on a different Mondrian, until the wavelengths were exactly the same as those that had been reflected by the blue rectangle on the original. When he showed this new Mondrian to his participants, the red rectangle looked—you guessed it—red, even though it reflected exactly the same wavelengths as had the blue rectangle on the original Mondrian.

The point of Land's demonstration is that blue objects stay blue, green objects stay green, and so forth, regardless of the wavelengths they reflect. This color constancy occurs as long as the object is illuminated with light that contains some short, medium, and long wavelengths (such as daylight, firelight, and virtually all manufactured lighting) and as long as the object is viewed as part of a scene, not in isolation.

According to Land's **retinex theory** of color vision, the color of an object is determined by its *reflectance*—the proportion of light of different wavelengths that a surface reflects. Although the wavelengths of light reflected by a surface change dramatically with changes in illumination, the efficiency with which a surface absorbs each wavelength and reflects the unabsorbed portion does not change. According to the retinex theory, the visual system calculates the reflectance of surfaces, and thus, perceives their colors, by comparing the light reflected by adjacent surfaces in at least three different wavelength bands (short, medium, and long). You learned in the previous module that the context plays an important role in the processing of spatial contrast (i.e., edges), and the retinex theory suggests that the context plays a similarly important role in processing color (Shevell & Kingdom, 2008).

Scan Your Brain

The striate cortex is the main entrance point of visual signals to the cortex. In the upcoming module, we will follow visual signals to other parts of the cortex. This is a good point to pause and review what you have learned. Draw a line to connect each term in the first column with the closely related word or phrase in the second column. Each term should be linked to only one item in the second column. The correct answers are provided at the end of this exercise. Before proceeding, review material related to your errors and omissions.

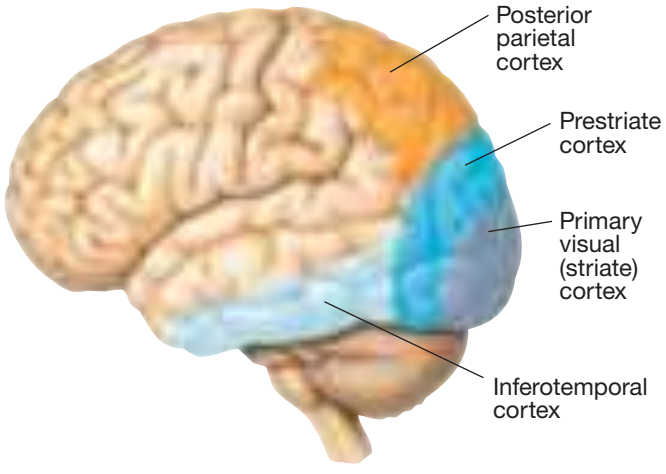
1. contrast enhancement	**a.** many are binocular
2. simple cortical cells	**b.** complementary afterimages
3. complex cortical cells	**c.** striate cortex
4. ocular dominance columns	**d.** reflectance
5. component	**e.** static on and off areas
6. opponent	**f.** three
7. retinex	**g.** Mach bands

Scan Your Brain answers: (1) g, (2) e, (3) a, (4) c, (5) f, (6) b, (7) d.

Cortical Mechanisms of Vision and Conscious Awareness

So far, you have followed the major visual pathways from the eyes to the primary visual cortex, but there is much more to the human visual system—we are visual animals. The entire occipital cortex as well as large areas of temporal cortex and parietal cortex are involved in vision (see Figure 6.20).

Figure 6.20 The visual areas of the human cerebral cortex.



Three Different Classes of Visual Cortex

LO 6.20 Describe the three classes of visual cortex and identify their locations in the brain.

Visual cortex is often considered to be of three different classes. *Primary visual cortex*, as you have learned, is that area of cortex that receives most of its input from the visual relay nuclei of the thalamus (i.e., from the lateral geniculate nuclei). Areas of **secondary visual cortex** are those that receive most of their input from the primary visual cortex, and areas of **visual association cortex** are those that receive input from areas of secondary visual cortex as well as from the secondary areas of other sensory systems.

The primary visual cortex is located in the posterior region of the occipital lobes, much of it hidden from view in the longitudinal fissure. Most areas of secondary visual cortex are located in two general regions: in the prestriate cortex and in the inferotemporal cortex. The **prestriate cortex** is the band of tissue in the occipital lobe that surrounds the primary visual cortex. The **inferotemporal cortex** is the cortex of the inferior temporal lobe. Areas of association cortex that receive visual input are located in several parts of the cerebral cortex, but the largest single area is in the **posterior parietal cortex**.

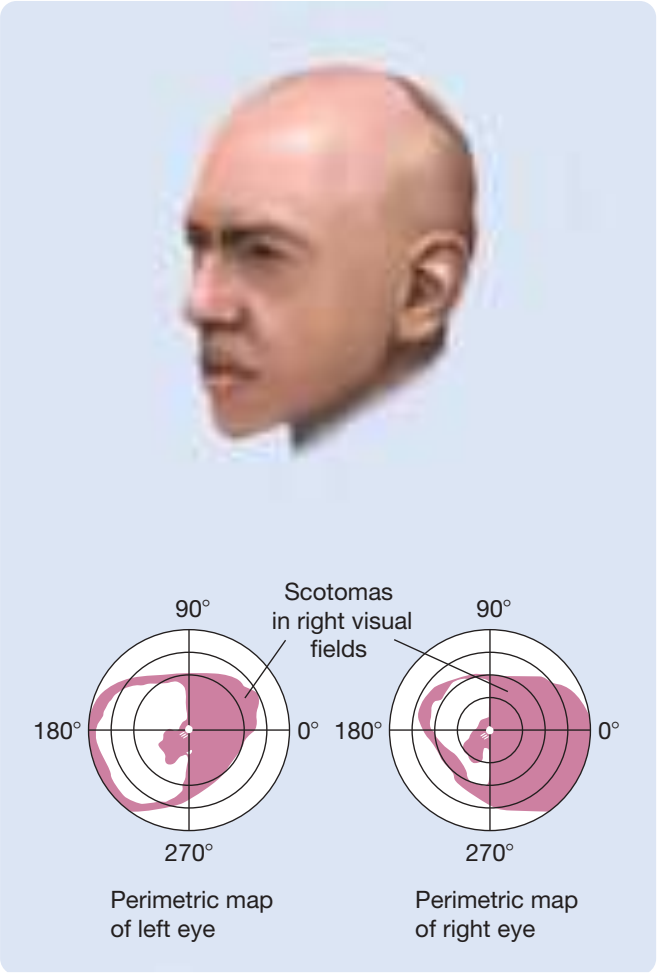
The major flow of visual information in the cortex is from primary visual cortex to the various areas of secondary visual cortex to the areas of association cortex. As one moves up this visual hierarchy, the neurons have larger receptive fields and the stimuli to which the neurons respond are more specific and more complex.

Damage to Primary Visual Cortex: Scotomas and Completion

LO 6.21 Explain what happens when an area of primary visual cortex is damaged.

Damage to an area of the primary visual cortex produces a **scotoma**—an area of blindness—in the corresponding area of the contralateral visual field of both eyes (see Figure 6.13). Neurological patients with suspected damage to the primary visual cortex are usually given a **perimetry test**. While the patient's head is held motionless on a chin rest, the patient stares with one eye at a fixation point on a screen. A small dot of light is then flashed on various parts of the screen, and the patient presses a button to record when the dot is seen. Then, the entire process is repeated for the other eye. The result is a map of the right and left visual field of each eye, which indicates any areas of blindness. Figure 6.21 illustrates the perimetric maps of each eye of a man with a bullet wound in his left primary visual cortex. Notice the massive scotoma in the right visual field of each eye.

Figure 6.21 The perimetric maps of a man with a bullet wound in his left primary visual cortex. The scotomas (areas of blindness) are indicated in purple.



Based on Teuber, H.-L., Battersby, W. S., & Bender, M. B. (1960). Recovery of function after brain injury in man. In *Outcomes of severe damage to the nervous system. CIBA Foundation Symposium 34*. Amsterdam, Netherlands: Elsevier North-Holland.

Many patients with scotomas are not consciously aware of their deficits. One factor that contributes to this lack of awareness is completion. A patient with a scotoma who looks at a complex figure, part of which lies in the scotoma, often reports seeing a complete image (see Silvanto, 2014). In some cases, this completion may depend on residual visual capacities in the scotoma; however, completion also occurs in cases in which this explanation can be ruled out. For example, patients who are **hemianopsic** (having a scotoma covering half of the visual field) may see an entire face when they focus on a person's nose, even when the side of the face in the scotoma has been covered by a blank card.

Consider the completion phenomenon experienced by the esteemed physiological psychologist Karl Lashley (1941). He often developed a large scotoma next to his fovea during migraine attacks (see Figure 6.22).

Figure 6.22 The completion of a migraine-induced scotoma, as described by Karl Lashley (1941).

Lashley's scotoma

What Lashley saw

Lashley (1941)

Blindsight is the ability to respond to visual stimuli in a scotoma with no conscious awareness of them (de Gelder, 2010; Leopold, 2012; Silvanto, 2014). Of all visual abilities, perception of motion is most likely to survive damage to primary visual cortex (see Schmid & Maier, 2015). For example, a patient with blindsight might reach out and grab a moving object in her scotoma, all the while claiming not to see the object.

If blindsight confuses you, imagine how it confuses people who experience it. Consider, for example, the reactions to blindsight of D.B., a patient who was blind in his left visual field following surgical removal of his right occipital lobe (Weiskrantz et al., 1974).

The Physiological Psychologist Who Made Faces Disappear

Talking with a friend, I [Karl Lashley, an early leader in brain-behavior research] glanced just to the right of his face wherein his head disappeared. His shoulders and necktie were still visible but the vertical stripes on the wallpaper behind him seemed to extend down to the necktie. It was impossible to see this as a blank area when projected on the striped wallpaper of uniformly patterned surface, although any intervening object failed to be seen. (Lashley, 1941, p. 338)

Journal Prompt 6.6

Earlier you learned about surface interpolation. How is surface interpolation at work in this case study? (Hint: Take a close look at Figure 6.22.)

You probably equate perception with **conscious awareness**; that is, you might assume that if a person sees something, he or she will be consciously aware of seeing it. In everyday thinking, perceiving and being aware are inseparable processes: We assume that someone who has seen something will be able to acknowledge that he or she has seen it and be able to describe it. In the following pages, you will encounter examples of phenomena for which this is not the case: people who see things but have no conscious awareness of them. Blindsight is the first example.

Blindsight is sometimes displayed by patients with scotomas resulting from damage to primary visual cortex.

The Case of D.B., the Man Confused by His Own Blindsight

D.B. had no awareness of "seeing" in his blind left field. Despite this apparent left-field blindness, he could accurately reach for visual stimuli in his left field and could accurately differentiate between a horizontal or diagonal line in his left field if forced to "guess." When he was questioned about his vision in his left field, his most usual response was that he saw nothing. When he was shown a video of his accurate left-field performance through his good, right field, he was astonished and insisted he was just guessing.

Two neurological interpretations of blindsight have been proposed. One is that the striate cortex is not completely destroyed and the remaining islands of functional cells are capable of mediating some visual abilities in the absence of conscious awareness (see Wüst, Kasten, & Sabel, 2002). The other is that those visual pathways that ascend directly to the secondary visual cortex from subcortical visual structures without passing through the primary visual cortex are capable of maintaining some visual abilities in the absence of cognitive awareness (see Schmid & Maier, 2015). There is some support for both theories, but it is far from conclusive in either case (see Gross, Moore, & Rodman, 2004; Rosa, Tweedale, & Elston, 2000; Schärli, Harman, & Hogben, 1999a, 1999b). Indeed, it is possible that both mechanisms contribute to the phenomenon.

Functional Areas of Secondary and Association Visual Cortex

LO 6.22 Describe the areas of secondary visual cortex and association cortex involved in vision.

Secondary visual cortex and the portions of association cortex involved in visual analysis are both composed of many different areas, each specialized for a particular type of visual analysis. For example, in the macaque monkey, whose visual cortex has been most thoroughly mapped, there are 32 different functional areas of visual cortex; in addition to primary visual cortex, 24 areas of secondary visual cortex and 7 areas of association visual cortex have been identified. The neurons in each functional area respond most vigorously to different aspects of visual stimuli (e.g., to their color, movement, or shape); selective lesions to the different areas produce different visual losses; and there are anatomical and organizational differences among the areas (see Patel et al., 2014).

The various functional areas of secondary and association visual cortex in the macaque are prodigiously interconnected. Anterograde and retrograde tracing studies have identified more than 300 interconnecting pathways (see Markov & Kennedy, 2013). Connections between areas are virtually always reciprocal (see Gilbert & Li, 2013).

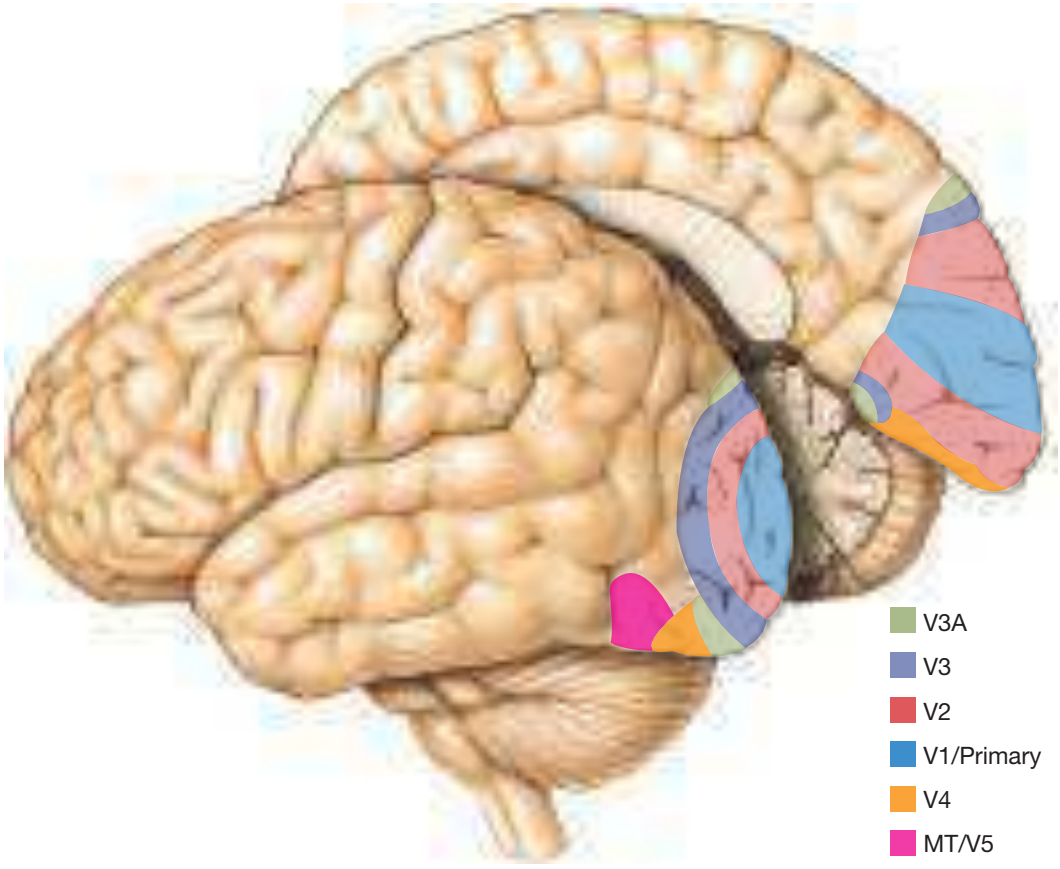
PET, fMRI, and evoked potentials (see Chapter 5) have been used to identify various areas of visual cortex in humans. The activity of volunteers' brains has been monitored while they inspect various types of visual stimuli. By identifying the areas of activation associated with various visual properties (e.g., movement or color), researchers have so far delineated about a dozen different functional areas of human visual cortex (see Grill-Spector & Mallach, 2004). A map of some of these areas is shown in Figure 6.23. Most are similar in terms of location, anatomical characteristics, and function to areas already identified in the macaque.

Dorsal and Ventral Streams

LO 6.23 Explain the difference between the dorsal and ventral streams and the functions that have been attributed to each stream by different theories.

As you have already learned, most visual information enters the primary visual cortex via the lateral geniculate nuclei. The information from the two lateral geniculate nuclei is received in the primary visual cortex, combined, and then segregated into multiple pathways that project separately to the various functional areas of secondary, and then association, visual cortex (see Horton & Sincich, 2004).

Figure 6.23 Some of the visual areas that have been identified in the human brain.



Many pathways that conduct information from the primary visual cortex through various specialized areas of secondary and association cortex can be thought of as components of two major streams: the dorsal stream and the ventral stream (Ungerleider & Mishkin, 1982). The **dorsal stream** flows from the primary visual cortex to the dorsal prestriate cortex to the posterior parietal cortex, and the **ventral stream** flows from the primary visual cortex to the ventral prestriate cortex to the inferotemporal cortex—see Figure 6.24.

Most visual cortex neurons in the dorsal stream respond most robustly to spatial stimuli, such as those indicating the location of objects or their direction of movement. In contrast, most neurons in the ventral stream respond to the characteristics of objects, such as color and shape (see Tompa & Sáry, 2010). Indeed, there are clusters of visual neurons in the ventral stream, and each cluster responds specifically to a particular class of objects—for example, most neurons in a particular cluster may respond to faces, whereas most neurons in another cluster might respond to animals (Haxby, 2006; Reddy & Kanwisher, 2006). Accordingly, Ungerleider and Mishkin (1982) proposed that the dorsal and ventral visual streams perform different visual functions. They suggested that the dorsal stream is involved in the perception of "where" objects are and the ventral stream is involved in the perception of "what" objects are.

A major implication of the **"where" versus "what" theory** of vision is that damage to some areas of cortex may abolish certain aspects of vision while leaving others unaffected. Indeed, the most convincing support for the influential "where" versus "what" theory has come from the comparison of the specific effects of damage to the dorsal and ventral streams (see Ungerleider & Haxby, 1994). Patients with damage to the posterior parietal cortex often have difficulty reaching accurately for objects they have no difficulty describing; conversely, patients with damage to the inferotemporal cortex often have no difficulty reaching accurately for objects they have difficulty describing.

Although the "where" versus "what" theory is widely accepted, there is an alternative interpretation for the same evidence (de Haan & Cowey, 2011; Haque et al., 2018; O'Reilly, 2010). Goodale and Milner (1992) argued that the primary difference between the dorsal and ventral streams is not the kinds of information they carry but the use to which that information is put. They suggested that the primary function of the dorsal stream is to direct behavioral interactions with objects, whereas the primary function of the ventral stream is to mediate the conscious perception of objects. Goodale and Milner's assertion has been termed the **"control of behavior" versus "conscious perception" theory** (see Logothetis & Sheinberg, 1996). One of the most interesting aspects of this theory is its evolutionary implication: Goodale (2004) suggested that the conscious awareness mediated by the ventral stream is one thing that distinguishes humans and their close relatives from their evolutionary ancestors.

The "control of behavior" versus "conscious perception" theory can readily explain the two major neuropsychological findings that are the foundation of the "where" versus "what" theory. Namely, the "control of behavior" versus "conscious perception" theory suggests that patients with dorsal stream damage may do poorly on tests of location and movement because most tests of location and movement involve performance measures, and that patients with ventral stream damage may do poorly on tests of visual recognition because most tests of visual recognition involve verbal responses, and thus, conscious awareness.

The major support for the "control of behavior" versus "conscious perception" theory is the confirmation of its two primary predictions: (1) that some patients with bilateral lesions to the ventral stream may have no conscious experience of seeing and yet be able to interact with objects under visual guidance, and (2) that some patients with bilateral lesions to the dorsal stream may consciously see objects but be unable to interact with them under visual guidance (see Figure 6.25). Following are two such cases.

Figure 6.24 Information about particular aspects of a visual display flow out of the primary visual cortex over many pathways. The pathways can be grouped into two general streams: dorsal and ventral.

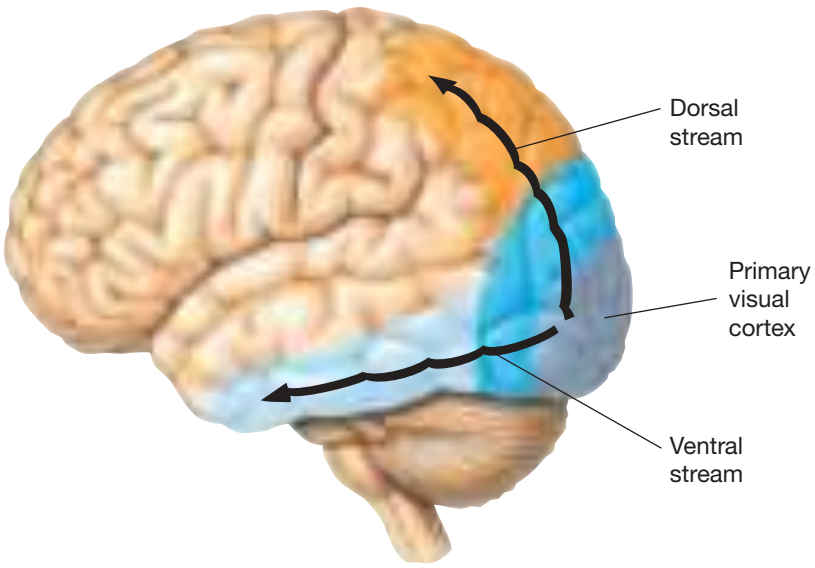
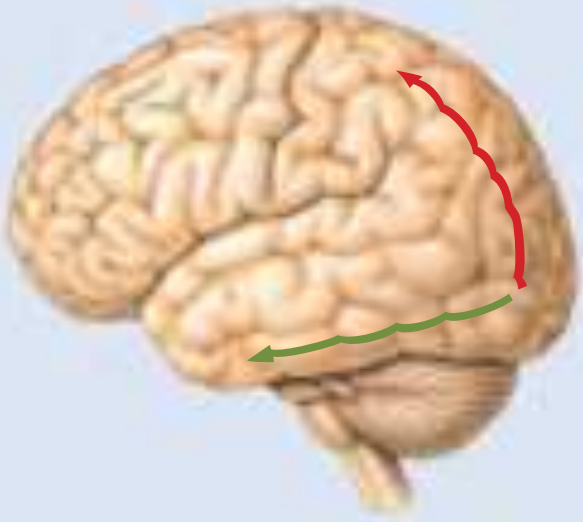


Figure 6.25 The "where" versus "what" and the "control of behavior" versus "conscious perception" theories make different predictions.

Dorsal and Ventral Streams: Two Theories and What They Predict



"Where" vs. "What" Theory

Dorsal stream specializes in visual spatial perception
Ventral stream specializes in visual pattern recognition

Predicts
- Damage to **dorsal stream** disrupts visual spatial perception
- Damage to **ventral stream** disrupts visual pattern recognition

"Control of Behavior" vs. "Conscious Perception" Theory

Dorsal stream specializes in visually guided behavior
Ventral stream specializes in conscious visual perception

Predicts
- Damage to **dorsal stream** disrupts visually guided behavior but not conscious visual perception
- Damage to **ventral stream** disrupts conscious visual perception but not visually guided behavior

D.F., the Woman Who Could Grasp Objects She Did Not Consciously See

D.F. has bilateral damage to her ventral prestriate cortex, thus interrupting the flow of the ventral stream; her case is described by Goodale and Milner (2004). Amazingly, she can respond accurately to visual stimuli that she does not consciously see.

> Despite her inability to consciously recognize the size, shape and orientation of visual objects, D.F. displayed accurate hand movements directed at the same objects. For example, when she was asked to indicate the width of blocks with her index finger and thumb, her matches were variable and unrelated to the actual size of the blocks. However, when she was asked to pick up blocks of different sizes, the distance between her index finger and thumb changed appropriately with the size of the object. In other words, D.F. adjusted her hand to the size of objects she was about to pick up, even though she did not consciously perceive their size.
>
> A similar dissociation occurred in her responses to the orientation of stimuli. When presented with a large slanted slot, she could not indicate the orientation of the slot either verbally or manually. However, she was as good as healthy volunteers at quickly placing a card in the slot, orienting her hand appropriately from the start of the movement.

A.T., the Woman Who Could Not Accurately Grasp Unfamiliar Objects That She Saw

The case of A.T. is in major respects complementary to that of D.F. A.T. is a woman with a lesion of the occipitoparietal region, which likely interrupts her dorsal route (Jeannerod et al., 1995).

A.T. was able to recognize objects and demonstrate their size with her fingers. In contrast, the preshape of her hand during object-directed movements was incorrect. As a consequence, she could not pick up objects between her fingertips—instead, the patient made awkward palmar grasps. Although A.T. could not preshape her hand to pick up neutral objects like blocks, when presented with a familiar object of standard size, like a lipstick, she grasped it with reasonable accuracy.

The widely held view that the dorsal stream controls visually guided behavior, whereas the ventral stream controls visual perception is currently under considerable scrutiny. For example, recent human and nonhuman studies have found that the dorsal stream carries information about objects (see Bi, Wang, & Caramazza, 2016; Freud, Plaut, & Behrmann, 2016) and that the ventral stream is active during interactions with objects (see Connor & Knierim, 2017). These findings are the exact opposite of the predictions of the "control of behavior" versus "conscious perception"

theory and instead suggest that both visual streams carry information about what an object is and how to interact with it. Accordingly, the dichotomy of two functional streams within the higher visual areas may no longer be tenable.

The remainder of this chapter focuses on two neuropsychological conditions, *prosopagnosia* and *akinetopsia*, and the damage to visual cortical areas associated with each of them. Prosopagnosia refers to a difficulty in recognizing faces; akinetopsia to a difficulty in perceiving visual motion. Damage to the *fusiform face area* or the *occipital face area* has been linked to *prosopagnosia*, whereas damage to area *MT* (middle temporal) has been linked to *akinetopsia*.

Prosopagnosia

LO 6.24 Describe the phenomenon of prosopagnosia and discuss the associated theoretical issues.

Prosopagnosia, briefly put, is a visual agnosia for faces (see DeGutis et al., 2014) that can be acquired either during development (*developmental prosopagnosia*) or as a result of brain injury (*acquired prosopagnosia*; see Susilo & Duchaine, 2013). Let us explain. **Agnosia** is a failure of recognition (*gnosis* means "to know") that is not attributable to a sensory deficit or to verbal or intellectual impairment. A **visual agnosia** is a specific agnosia for visual stimuli. In other words, visual agnosics can see things, but they don't know what they are (see Albonico & Barton, 2019).

Visual agnosias are often specific to a particular aspect of visual input and are named accordingly; for example, *movement agnosia*, *object agnosia*, and *color agnosia* are difficulties in recognizing movement, objects, and color, respectively.

Prosopagnosics are visual agnosics with a specific difficulty in recognizing faces. They can recognize a face as a face, but they have problems recognizing whose face it is. In extreme cases, prosopagnosics cannot recognize themselves in photos.

IS PROSOPAGNOSIA SPECIFIC TO FACES? The belief that prosopagnosia is a deficit specific to the recognition of faces has been challenged. To understand this challenge, you need to know that the diagnosis of prosopagnosia is typically applied to neuropsychological patients who have difficulty recognizing particular faces but can readily identify other test objects (e.g., a chair, a dog, or a tree). Surely, this is powerful evidence that prosopagnosics have recognition difficulties specific to faces. Not so. Pause for a moment and think about this evidence: It is seriously flawed.

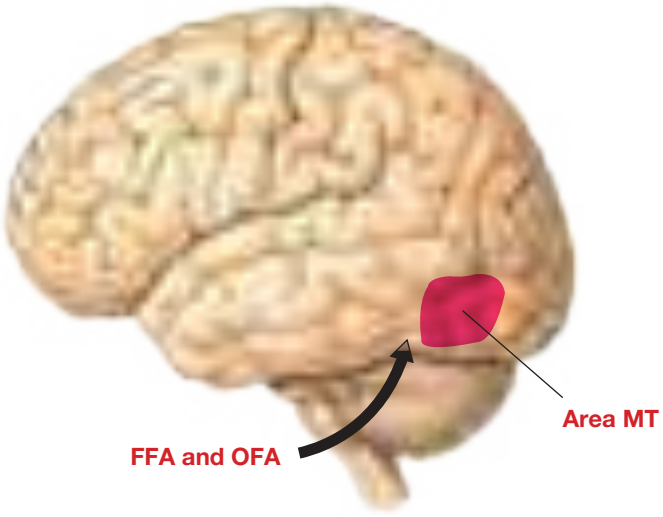
Because prosopagnosics have no difficulty recognizing faces as faces, the fact that they can recognize chairs as chairs, pencils as pencils, and doors as doors is not relevant. The critical question is whether they can recognize which chair, which pencil, and which door. Careful testing of this sort usually reveals that their recognition deficits are not restricted to faces: For example, a farmer lost his ability to recognize particular cows when he lost his ability to recognize faces. This suggests that some prosopagnosic patients have a general problem recognizing specific objects that belong to complex classes of objects (e.g., particular automobiles or particular houses), not a specific problem recognizing faces (see Behrmann et al., 2005)—although in daily life the facial-recognition problems are likely to be the most problematic and, thus, obvious. Still, it is difficult to rule out the possibility that at least a few prosopagnosic patients have recognition deficits limited to faces. Indeed, several thorough case studies of prosopagnosia have failed to detect recognition deficits unrelated to faces (Duchaine & Nakayama, 2005). It seems likely that prosopagnosia is not a unitary disorder (Duchaine & Nakayama, 2006), and it appears that only some patients with this diagnosis have pattern-recognition deficits restricted to facial recognition (see Albonico & Barton, 2019; Robotham & Starrfelt, 2018).

R.P., a Typical Prosopagnosic

With routine testing, R.P. displayed a severe deficit in recognizing faces and in identifying facial expressions (Laeng & Caviness, 2001) but no other obvious recognition problems. If testing had stopped there, as it often does, it would have been concluded that R.P. is an agnosic with recognition problems specific to human faces. However, more thorough testing indicated that R.P. is deficient in recognizing all objects with complex curved surfaces, not just faces.

WHAT BRAIN PATHOLOGY IS ASSOCIATED WITH PROSOPAGNOSIA? The diagnosis of acquired prosopagnosia is usually associated with damage to either or both of the *fusiform face area* and the *occipital face area* (see Haque et al., 2018). The **fusiform face area (FFA)** is located on the ventral surface of the boundary between the occipital and temporal lobes (see Figure 6.26). The FFA has been implicated in face identification because parts of it are selectively activated by human faces (see Collins & Olson, 2014; van den Hurk et al., 2015) and because electrical stimulation of this brain area in humans can metamorphose a viewed face into a completely different face (see Rangarajan et al., 2014). The **occipital face area (OFA)** is located on the ventral surface of the occipital lobe (see Figure 6.26). Reversible inactivation of the OFA by transcranial magnetic stimulation selectively disrupts the ability to discriminate between faces (see Freiwald, Duchaine, & Yovel, 2016). In addition to the FFA and OFA, recent evidence also

Figure 6.26 The location of the fusiform face area (FFA), the occipital face area (OFA), and area MT. Damage to the FFA or OFA is associated with prosopagnosia. Damage to area MT is associated with akinetopsia. The FFA and OFA are not visible in this figure; they lie on the ventral surface of the temporal lobe and occipital lobe, respectively.



points to an important role of the *lateral prefrontal cortex* in face identification (see Kornblith & Tsao, 2017). It makes sense that specialized mechanisms to perceive faces have evolved in the human brain because face perception plays such a major role in human social behavior (see Freiwald, Duchaine, & Yovel, 2016; Jack & Schyns, 2017; Powell, Kosakowski, & Saxe, 2018).

CAN PROSOPAGNOSICS PERCEIVE FACES IN THE ABSENCE OF CONSCIOUS AWARENESS? Tranel and Damasio (1985) were the first to demonstrate that prosopagnosics can recognize faces in the absence of conscious awareness. They presented a series of photographs to several patients, some familiar to the patients, some not. The patients claimed not to recognize any of the faces. However, when familiar faces were presented, the subjects displayed a large skin conductance response, which did not occur with unfamiliar faces, thus indicating that the faces were being unconsciously recognized by undamaged portions of the brain.

Akinetopsia

LO 6.25 Describe the phenomenon of akinetopsia and discuss the associated theoretical issues.

Akinetopsia is a deficiency in the ability to see movement progress in a normal smooth fashion—individuals affected by it only see periodic snapshots of the world. Akinetopsia can be either a permanent result of brain damage, or it can be the transient result of taking high doses of certain antidepressants (Haque et al., 2018; Horton, 2009).

Two Cases of Drug-Induced Akinetopsia

A 47-year-old depressed male receiving 100 mg of nefazodone twice daily reported a bizarre derangement of motion perception. Each moving object was followed by a trail of multiple freeze-frame images, which disappeared once the motion ceased. A 48-year-old female receiving 400 mg of nefazodone once daily at bedtime reported similar symptoms, with persistent multiple strobelike trails following moving objects. In both cases, stationary elements were perceived normally, indicating a selective impairment of the visual perception of motion. Vision returned to normal in both patients once the dosage was reduced.

When akinetopsia is the result of an acquired brain injury, it is often associated with damage to **area MT** (middle temporal area) of the cortex. The location of MT—near the junction of the temporal, parietal, and occipital lobes—is illustrated in Figure 6.26.

The function of MT appears to be the perception of motion. Given the importance of the perception of motion in primate survival, it is reasonable that an area of the visual system is dedicated to it. Some neurons at lower levels of the visual hierarchy (e.g., in the primary visual cortex) respond to movement as well as color and shape; however, they provide little information about the direction of movement because their receptive fields are so small. In contrast, 95 percent of the neurons of MT respond to specific directions of movement and little else. Also, each MT neuron has a large binocular receptive field, allowing it to track movement over a wide range.

The following four lines of research implicate MT in the visual perception of motion and damage to MT as a cause of akinetopsia:

- Patients with akinetopsia tend to have unilateral or bilateral damage to MT (Cooper et al., 2012; Haque et al., 2018).
- As measured by fMRI, activity in MT increases when humans view movement (see Haque et al., 2018; Zeki, 2015).
- Blocking activity in MT with transcranial magnetic stimulation (TMS) produces motion blindness (see Haque et al., 2018; Vetter, Grosbras, & Muckli, 2015).
- Electrical stimulation of MT in human patients induces the visual perception of motion (Blanke et al., 2002).

Themes Revisited

Vision is a creative process. Your visual system does not transmit complete and intact visual images of the world to the cortex. It carries information about a few critical features of the visual field—for example, information about location, movement, brightness contrast, and color contrast—and from these bits of information, it creates a perception far better than the retinal image in all respects and better than the external reality in some. Another main point is that your visual system can perceive things without your conscious awareness of them.

The Check It Out demonstrations in this chapter offered you many opportunities to experience firsthand important aspects of the visual process. We hope you checked them out and your experience made you more aware of the amazing abilities of your own visual system and the relevance of what you have learned in this chapter to your everyday life.

This chapter developed all four of the major themes. First, the evolutionary perspective theme was emphasized, largely because the majority of research on the neural mechanisms of human vision has been comparative and because thinking about the adaptiveness of various aspects of vision (e.g., color vision) has led to important insights.

Second, the thinking creatively theme was emphasized because the main point of the chapter was that we tend to think about our own visual systems in a way that is fundamentally incorrect: The visual system does not passively provide images of the external world; it extracts some features of the external world, and from these it creates our visual perceptions. Once you learn to think in this unconventional way, you will be able to better appreciate the amazingness of your own visual system.

Third, the clinical implications theme was developed through a series of clinical case studies: Mrs. Richards, who experienced fortification illusions before her migraine attacks; Karl Lashley, the physiological psychologist who used his scotoma to turn a friend's head into a wallpaper pattern; D.B., the man with blindsight; D.F., who showed by her accurate reaching that she detected the size, shape, and orientation of objects that she could not describe; A.T., who could describe the size and shape of objects she could not accurately reach for; R.P., a typical prosopagnosic; and two patients with akinetopsia induced by a particular antidepressant.

Fourth, this chapter touched on the neuroplasticity theme. The study of the visual system has focused on the receptive field properties of neurons in response to simple stimuli, and receptive fields have been assumed to be static. However, when natural visual scenes have been used in such studies, it has become apparent that each neuron's receptive field changes depending on the visual context.

This chapter was also filled with materials related to one of the emerging themes: consciousness. Two examples are the discussion of the distinction between the dorsal and ventral visual streams, and the unconscious processing of visual stimuli in cases of scotomas, blindsight, and prosopagnosia.

Key Terms

Light Enters the Eye and Reaches the Retina

Sensitivity, p. 155
Acuity, p. 155
Ciliary muscles, p. 155
Accommodation, p. 155
Binocular disparity, p. 156

The Retina and Translation of Light into Neural Signals

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Area MT, p. 180

Chapter 7

Sensory Systems, Perception, and Attention

How You Know the World

Barry Diomede/Alamy Stock Photo

Chapter Overview and Learning Objectives

Principles of Sensory System Organization	**LO 7.1** Name and define the three types of sensory cortex.
	LO 7.2 In the context of sensory system organization, explain what is meant by each of the following terms: *hierarchical organization*, *functional segregation*, and *parallel processing*. Summarize the current model of sensory system organization.
Auditory System	**LO 7.3** Explain the relationship between the physical and perceptual dimensions of sound.
	LO 7.4 Describe the components of the human ear, and explain how sound is processed within its various structures.
	LO 7.5 Describe the major pathways that lead from the ear to the primary auditory cortex.

	LO 7.6 Describe the organization of auditory cortex.
	LO 7.7 Describe the effects of damage to the auditory system.
Somatosensory System: Touch and Pain	**LO 7.8** Name some of the cutaneous receptors and explain the functional significance of fast versus slow receptor adaptation.
	LO 7.9 Describe the two major somatosensory pathways.
	LO 7.10 Describe the cortical somatosensory areas and their somatotopic layout.
	LO 7.11 Name the areas of association cortex that somatosensory signals are sent to, and describe the functional properties of one of those areas.
	LO 7.12 Describe the two major types of somatosensory agnosia.
	LO 7.13 Describe the rubber-hand illusion and its neural mechanisms.
	LO 7.14 Explain why the perception of pain is said to be paradoxical.
	LO 7.15 Define neuropathic pain and describe some of its putative neural mechanisms.
Chemical Senses: Smell and Taste	**LO 7.16** Describe two adaptive roles for the chemical senses.
	LO 7.17 Describe the olfactory system.
	LO 7.18 Describe the gustatory system.
	LO 7.19 Explain the potential effects of brain damage on the chemical senses.
Perception	**LO 7.20** Use examples to illustrate the role of experience in perception.
	LO 7.21 Explain perceptual decision making, using some examples of phantom percepts to illustrate.
	LO 7.22 Explain the binding problem and describe two potential solutions to it.
Selective Attention	**LO 7.23** Describe the two characteristics of selective attention and explain what is meant by exogenous versus endogenous attention.
	LO 7.24 Describe the phenomenon of change blindness.
	LO 7.25 Describe the neural mechanisms of attention.
	LO 7.26 Describe the disorder of attention known as simultanagnosia.

Two chapters in this text focus on the five human exteroceptive sensory systems: Chapter 6 and this one. Whereas Chapter 6 introduced the visual system, this chapter focuses on the remaining four of our five **exteroceptive sensory systems** (sensory systems that detect stimuli outside of our bodies): the *auditory* (hearing), *somatosensory* (touch), *olfactory* (smell), and *gustatory* (taste) systems.

Although we focus on the five human exteroceptive senses in this book, it is important to realize that there are other sorts of exteroceptive senses that we don't have. For example, many species can sense the earth's magnetic field and use that information to navigate (see Nordmann, Hochstoeger, & Keays, 2017). In addition, sharks, electric fish, and many amphibians detect minute electrical signals,

and use them for navigation, hunting, and communication (see Bellono, Leitch, & Julius, 2017).

In addition to covering the mechanisms of various sorts of **sensation** (the process of detecting the presence of stimuli), this chapter also discusses mechanisms of **perception**: the higher-order process of integrating, recognizing, and interpreting patterns of sensations. Although you will encounter examples of perception in the second, third, and fourth modules, the topic of perception is the focus of the fifth module. The chapter ends with an overview of the mechanisms of attention: how our brains manage to attend to a select few sensory stimuli despite being continuously bombarded by thousands of them.

Before you begin the first module of this chapter, consider the following case (Williams, 1970). As you read the chapter, think about this patient, the nature of his deficit, and the likely location of his brain damage. By the time you have reached the final module of this chapter, you will better understand this patient's problem.

The Case of the Man Who Could See Only One Thing at a Time

A 68-year-old patient was referred because he had difficulty finding his way around—even around his own home. The patient attributed his problems to his "inability to see properly." It was found that if two objects (e.g., two pencils) were held in front of him at the same time, he could see only one of them, whether they were held side by side, one above the other, or even one partially behind the other. Pictures of single objects or faces could be identified, even when quite complex; but if a picture included two objects, only one object could be identified at a time—he would perceive the first object, after which it would be replaced by a perception of the second object, which would then be replaced by a perception of the first object, and so on. If the patient was shown overlapping drawings (i.e., one drawn on top of another), he would see one but deny the existence of the other.

Principles of Sensory System Organization

The visual system is by far the most thoroughly studied sensory system. As a result, it is also the best understood. However, as more has been discovered about the other sensory systems, it has become apparent that each is organized like the visual system in fundamental ways.

Types of Sensory Areas of Cortex

LO 7.1 **Name and define the three types of sensory cortex.**

The sensory areas of the cortex are, by convention, considered to be of three fundamentally different types: primary, secondary, and association. The **primary sensory cortex** of a system is the area of sensory cortex that receives most of its input directly from the thalamic relay nuclei of that system. For example, as you learned in Chapter 6, the primary visual cortex is the area of the cerebral cortex that receives most of its input from the lateral geniculate nucleus of the thalamus. The **secondary sensory cortex** of a system comprises the areas of the sensory cortex that receive most of their input from the primary sensory cortex of that system or from other areas of secondary sensory cortex of the same system. **Association cortex** is any area of cortex that receives input from more than one sensory system. Most input to areas of association cortex comes via areas of secondary sensory cortex.

The interactions among these three types of sensory cortex and among other sensory structures are characterized by three major principles: hierarchical organization, functional segregation, and parallel processing.

Features of Sensory System Organization

LO 7.2 **In the context of sensory system organization, explain what is meant by each of the following terms: *hierarchical organization*, *functional segregation*, and *parallel processing*. Summarize the current model of sensory system organization.**

Sensory systems are characterized by **hierarchical organization**. A hierarchy is a system whose members can be assigned to specific levels or ranks in relation to one another. For example, an army is a hierarchical system because all soldiers are ranked with respect to their authority. In the same way, sensory structures are organized in a hierarchy on the basis of the specificity and complexity of their function. As one moves through a sensory system from receptors, to thalamic nuclei, to primary sensory cortex, to secondary sensory cortex, to association cortex, one finds neurons that respond optimally to stimuli of greater and greater specificity and complexity. Each level of a sensory hierarchy receives much of its input from lower levels and adds another layer of analysis before passing it on up the hierarchy (see Rees, Kreiman, & Koch, 2002).

The hierarchical organization of sensory systems is apparent from a comparison of the effects of damage to various levels: The higher the level of damage, the more specific and complex the deficit. For example, destruction of a sensory system's receptors produces a complete loss of ability to perceive in that sensory modality (e.g., total blindness or deafness); in contrast, destruction of an area of association or secondary sensory cortex typically produces complex and specific sensory deficits, while leaving fundamental sensory abilities intact. Dr. P., the man who mistook his wife for a hat (Sacks, 1985), displayed such a pattern of deficits.

Case of the Man Who Mistook His Wife for a Hat*

Dr. P. was a highly respected musician and teacher—a charming and intelligent man. He had been referred to the eminent neurologist Oliver Sacks for help with a vision problem. At least, as Dr. P. explained to the neurologist, other people seemed to think that he had a vision problem, and he did admit that he sometimes made odd errors.

Dr. Sacks tested Dr. P.'s vision and found his visual acuity to be excellent—Dr. P. could easily spot a pin on the floor. The first sign of a problem appeared when Dr. P. needed to put his shoe back on following a standard reflex test. Gazing at his foot, he asked Sacks if it was his shoe.

Continuing the examination, Dr. Sacks showed Dr. P. a glove and asked him what it was. Taking the glove and puzzling over it, Dr. P. could only guess that it was a container divided into five compartments for some reason. Even when Sacks asked whether the glove might fit on some part of the body, Dr. P. displayed no signs of recognition.

At that point, Dr. P. seemed to conclude that the examination was over and, from the expression on his face, that he had done rather well. Preparing to leave, he turned and grasped his wife's head and tried to put it on his own. Apparently, he thought it was his hat.

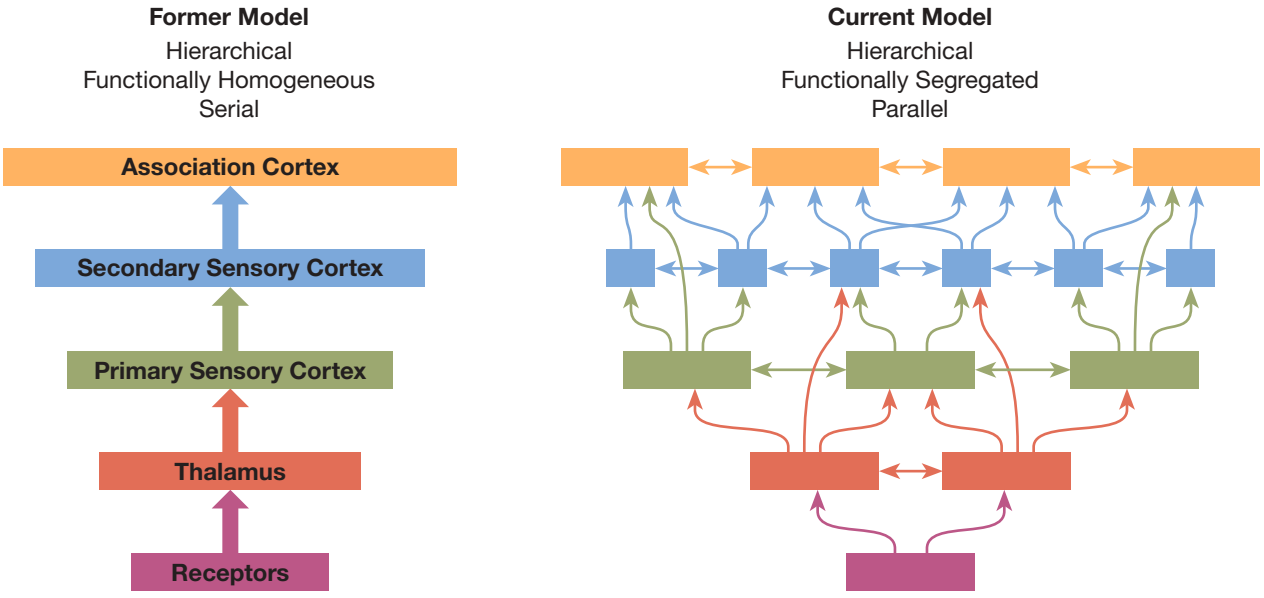
Mrs. P. showed little surprise. That kind of thing happened a lot.

FUNCTIONAL SEGREGATION. It was once assumed that the primary, secondary, and association areas of a sensory system were each *functionally homogeneous*. That is, it was assumed that all areas of cortex at any given level of a sensory hierarchy acted together to perform the same function. However, research has shown that **functional segregation**, rather than functional homogeneity, characterizes the organization of sensory systems. It is now clear that each of the three levels of cerebral cortex—primary, secondary, and association—in each sensory system contains functionally distinct areas that specialize in different kinds of analysis.

PARALLEL PROCESSING. It was once believed that the different levels of a sensory hierarchy were connected in a serial fashion. In a *serial system*, information flows among the components over just one pathway, like a string through a strand of beads. However, we now know that sensory systems are *parallel systems* in which information flows through the components over multiple pathways (see Lleras et al., 2017). Parallel systems feature **parallel processing**—the simultaneous analysis of a signal in different ways by the multiple parallel pathways of a neural network.

SUMMARY MODEL OF SENSORY SYSTEM ORGANIZATION. Figure 7.1 summarizes the information in this module by illustrating how thinking about the organization of sensory systems has changed. In the 1960s, sensory systems were believed to be hierarchical, functionally homogeneous,

Figure 7.1 Two models of sensory system organization: The former model was hierarchical, functionally homogeneous, and serial; the current model, which is more consistent with the evidence, is hierarchical, functionally segregated, and parallel. Not shown in the current model are the many descending pathways—one means by which higher levels of sensory systems can influence sensory input.



*Based on *The Man Who Mistook His Wife for a Hat and Other Clinical Tales* by Oliver Sacks. Copyright © 1970, 1981, 1983, 1984, 1986 by Oliver Sacks.

Figure 7.2 The relation between the physical and perceptual dimensions of sound.

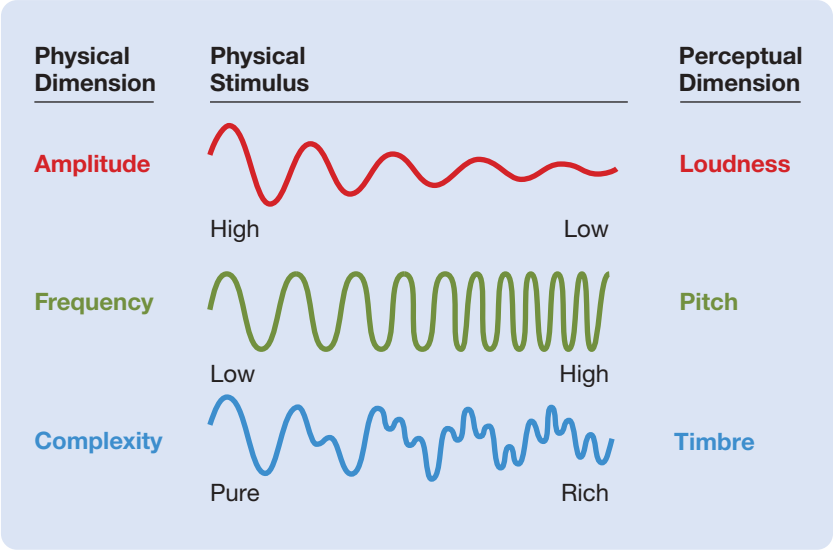
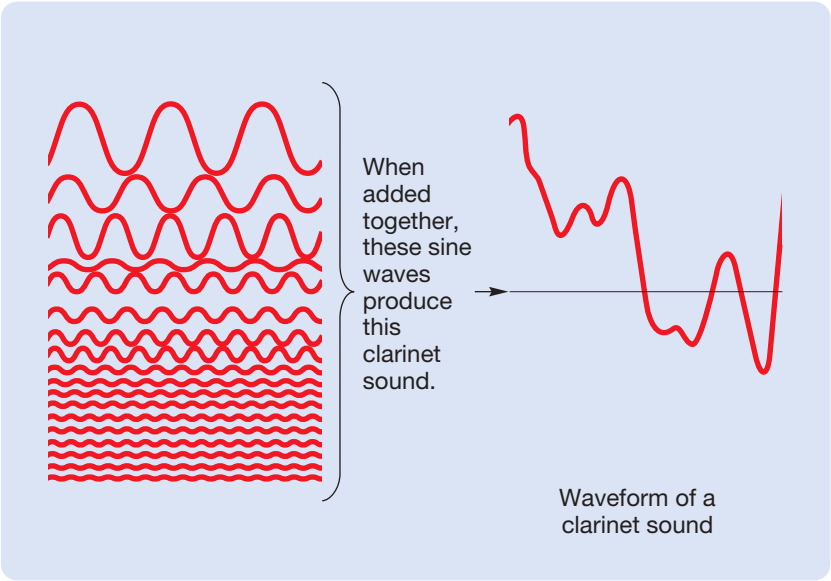


Figure 7.3 The breaking down of a sound—in this case, the sound of a clarinet—into its component sine waves by Fourier analysis. When added together, the component sine waves produce the complex sound wave.



and serial. However, subsequent research has established that sensory systems are hierarchical, functionally segregated, and parallel (see Rauschecker, 2015).

Not shown in Figure 7.1 are the many neurons that descend through the sensory hierarchies. Although sensory systems carry information from lower to higher levels of their respective hierarchies, they also conduct information in the opposite direction (from higher to lower levels). These are known as *top-down signals* (see Bressler & Richter, 2015; Marques et al., 2018; Ruff, 2013).

Now that you have an understanding of the general principles of sensory system organization, let's take a look in sequence at the auditory system, the somatosensory system, and the chemical sensory systems (smell and taste).

Auditory System

The function of the auditory system is the perception of sound. Sounds are vibrations of air molecules that stimulate the auditory system; humans hear only those molecular vibrations between about 20 and 20,000 *hertz* (cycles per second).

Physical and Perceptual Dimensions of Sound

LO 7.3 **Explain the relationship between the physical and perceptual dimensions of sound.**

Figure 7.2 illustrates how sounds are commonly recorded in the form of waves and the relation between the physical dimensions of sound vibrations and our perceptions of them. The *amplitude*, *frequency*, and *complexity* of the molecular vibrations are most closely linked to perceptions of *loudness*, *pitch*, and *timbre*, respectively.

Pure tones (sine wave vibrations) exist only in laboratories and sound recording studios; in real life, sound is always associated with complex patterns of vibrations. For example, Figure 7.3 illustrates the complex sound wave associated with one note of a clarinet. The figure also illustrates that any complex sound wave can be broken down mathematically into a series of sine waves of various frequencies and amplitudes; these component sine waves produce the original sound when they are added together. **Fourier analysis** is the mathematical procedure for breaking down complex waves into their component sine waves. One theory of audition is that the auditory system performs a Fourier-like analysis of complex sounds in terms of their component sine waves.

For any pure tone, there is a close relationship between the frequency of the tone and its perceived pitch; however, the relation between the frequencies that make up natural sounds (which are always composed of a mixture of frequencies) and their perceived pitch is complex (see Bidelman & Grall, 2014): The pitch of such sounds is

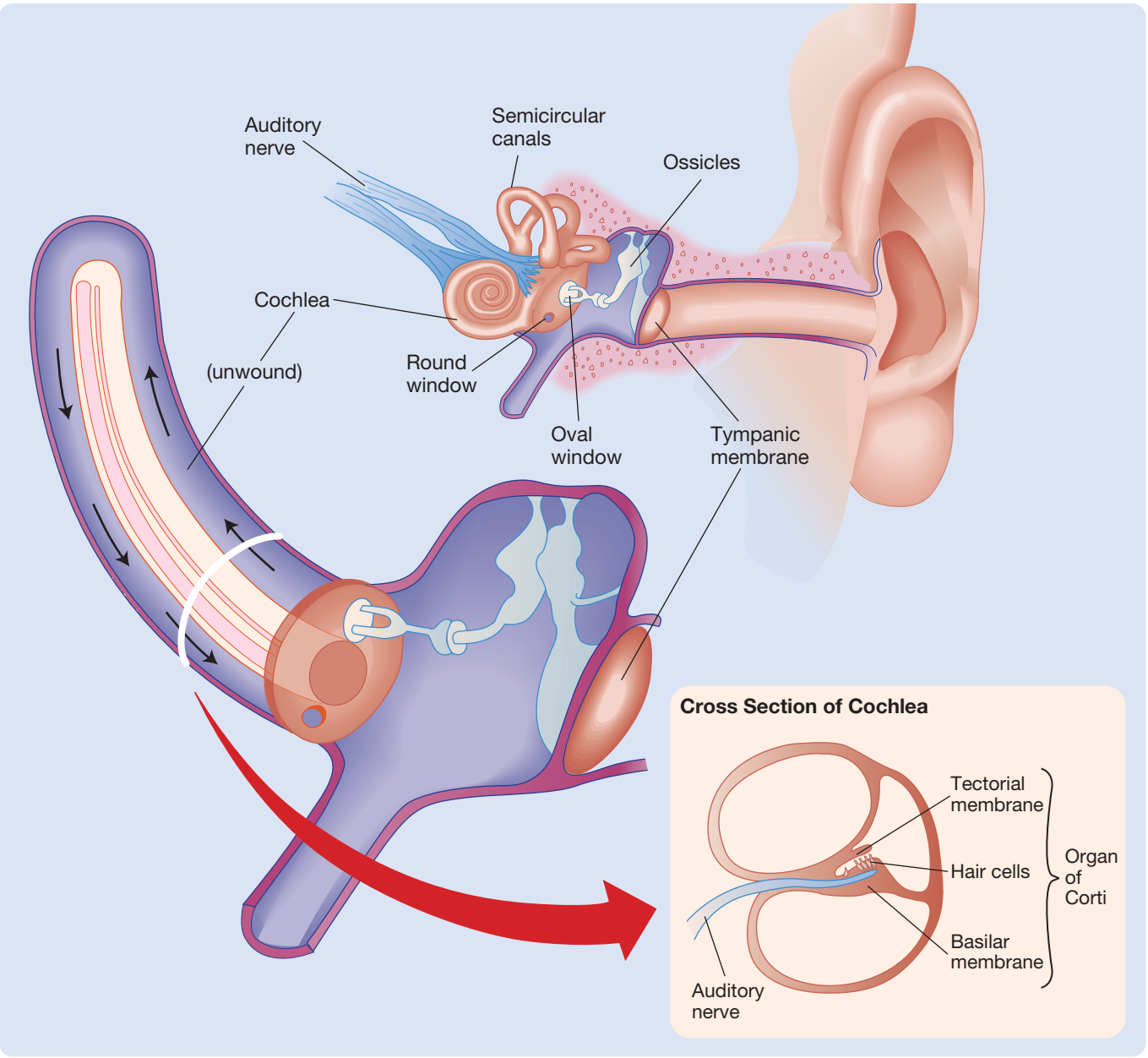
related to their *fundamental frequency*: the frequency that is the highest common *divisor* (a number that divides another number) for the various component frequencies. For example, a sound that is a mixture of 100, 200, and 300 Hz frequencies normally has a pitch related to 100 Hz because 100 Hz is the highest common divisor of the three components. An extremely important characteristic of pitch perception is the fact that the pitch of a complex sound may not be directly related to the frequency of any of the sound's components (see Lau & Werner, 2014). For example, a mixture of pure tones with frequencies of 200, 300, and 400 Hz would be perceived as having the same pitch as a pure tone of 100 Hz—because 100 Hz is the fundamental frequency (i.e., the highest common divisor) of 200, 300, and 400 Hz. This important aspect of pitch perception is referred to as the *missing fundamental* (see Oxenham, 2018).

The Ear

LO 7.4 **Describe the components of the human ear, and explain how sound is processed within its various structures.**

The ear is illustrated in Figure 7.4. Sound waves travel from the outer ear down the auditory canal and cause the **tympanic membrane** (the eardrum) to vibrate.

Figure 7.4 Anatomy of the ear.



These vibrations are then transferred to the three **ossicles**—the small bones of the middle ear: the *malleus* (the hammer), the *incus* (the anvil), and the *stapes* (the stirrup). The vibrations of the stapes trigger vibrations of the membrane called the **oval window**, which in turn transfers the vibrations to the fluid of the snail-shaped **cochlea** (*kokhlos* means "land snail"). The cochlea is a long, coiled tube with an internal structure running almost to its tip. This internal structure is the auditory receptor organ, the **organ of Corti**.

Each pressure change at the oval window travels along the organ of Corti as a wave. The organ of Corti is composed of several membranes; we will focus on two of them: the basilar membrane and the tectorial membrane. The auditory receptors, the **hair cells**, are mounted in the **basilar membrane**, and the **tectorial membrane** rests on the hair cells. Accordingly, a deflection of the organ of Corti at any point along its length produces a shearing force on the hair cells at the same point. This force stimulates the hair cells, which in turn increase firing in axons of the **auditory nerve** (see Wu et al., 2017)—a branch of the *auditory-vestibular nerve* (one of the 12 cranial nerves). The vibrations of the cochlear fluid are ultimately dissipated by the *round window*, an elastic membrane in the cochlear wall.

The cochlea is remarkably sensitive (see Hudspeth, 2014). Humans can hear differences in pure tones that differ in frequency by only 0.2 percent. The major principle of cochlear coding is that different frequencies produce maximal stimulation of hair cells at different points along the basilar membrane—with higher frequencies producing greater activation closer to the windows and lower frequencies producing greater activation at the tip of the basilar membrane. Thus, the many component frequencies that compose each complex sound activate hair cells at many different points along the basilar membrane, and the many signals created by a single complex sound are carried out of the ear by many different auditory neurons. Like the cochlea, most other structures of the auditory system are arrayed according to frequency. Thus, in the same way that the organization of the visual system is largely **retinotopic**, the organization of the auditory system is largely **tonotopic** (see Schreiner & Polley, 2014).

This brings us to the major unsolved mystery of auditory processing. Imagine yourself in a complex acoustic environment such as a party. The music is playing; people are dancing, eating, and drinking; and numerous conversations are going on around you. Because the component frequencies in each individual sound activate many sites along your basilar membrane, the number of sites simultaneously activated at any one time by the party noises is enormous. But somehow your auditory system manages to sort these individual frequency messages into separate categories and combine them so that you hear each source of complex sounds independently (see Bremen & Middlebrooks, 2013; Christison-Lagay & Cohen, 2014; Christison-Lagay, Gifford, & Cohen, 2015). For example, you hear the speech of the person standing next to you as a separate sequence of sounds, despite the fact that it contains many of the same component frequencies coming from other sources. The mechanism underlying this important ability has yet to be identified, but one theory is that it is due to the synchronous relationship over time of the frequency elements of each sound source (see Oxenham, 2018).

Figure 7.4 also shows the **semicircular canals**—the receptive organs of the **vestibular system**. The vestibular system carries information about the direction and intensity of head movements, which helps us maintain our balance (see Brandt & Dieterich, 2017; Gu, 2018).

From the Ear to the Primary Auditory Cortex

LO 7.5 Describe the major pathways that lead from the ear to the primary auditory cortex.

There is no major auditory pathway to the cortex comparable to the visual system's retina-geniculate-striate pathway. Instead, there is a network of auditory pathways, some of which are illustrated in Figure 7.5. The axons of each *auditory nerve* synapse in the ipsilateral *cochlear nuclei*, from which many projections lead to the **superior olives** on both sides of the brain stem at the same level. The axons of the olivary neurons project via the *lateral lemniscus* to the **inferior colliculi**, where they synapse on neurons that project to the **medial geniculate nuclei** of the thalamus, which in turn project to the *primary auditory cortex*. Notice that signals from each ear are combined at a very low level (in the superior olives) and are transmitted to both ipsilateral and contralateral auditory cortex.

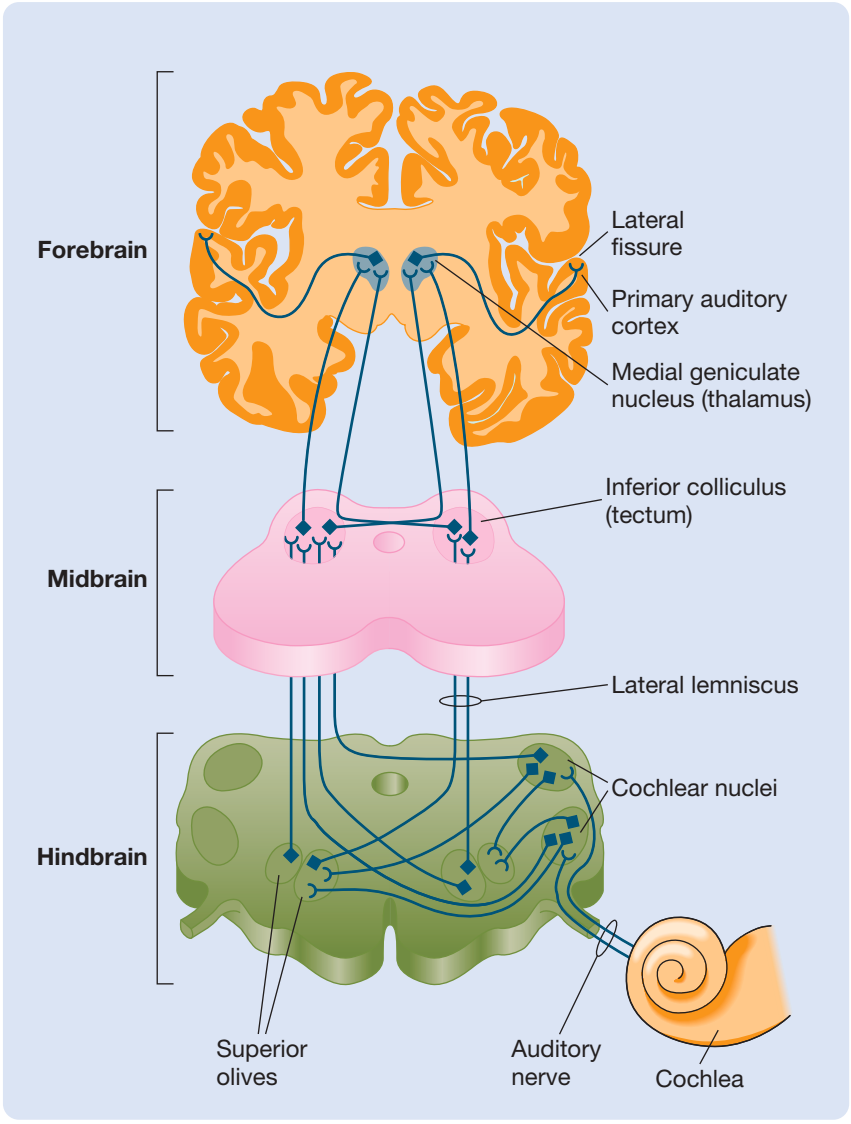
The subcortical pathways of the auditory system are inherently complex, and they have many more synapses than the other senses (see Jasmin, Lima, & Scott, 2019; Wang, 2018). Some researchers believe that the complex subcortical organization of the auditory system is related to the complexity of the analyses that the auditory system has to perform (see Wang, 2018).

Auditory Cortex

LO 7.6 Describe the organization of auditory cortex.

Recent progress in the study of human auditory cortex has resulted from the convergence of functional brain-imaging studies in humans and invasive neural recording studies in monkeys (see Saenz & Langers, 2014). Still, primate auditory cortex is far from being well understood—for example, our understanding of it lags far behind our current understanding of the visual cortex.

Figure 7.5 Some of the pathways of the auditory system that lead from one ear to the cortex.

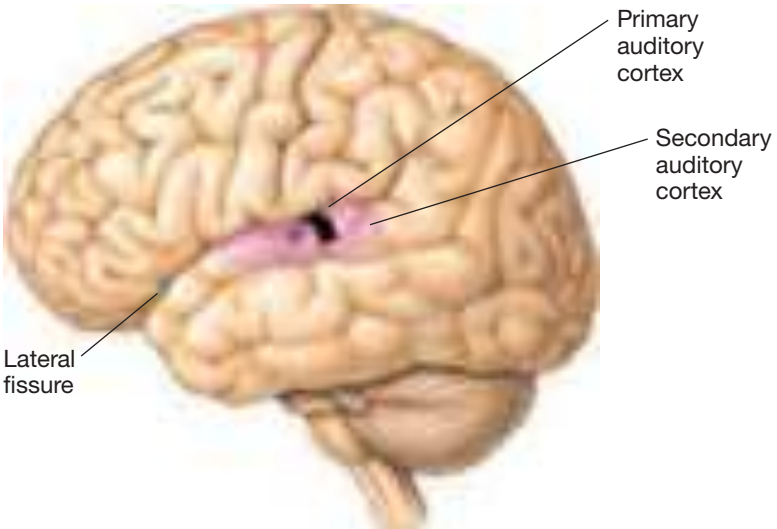


In primates, the primary auditory cortex, which receives the majority of its input from the medial geniculate nucleus, is located in the temporal lobe, hidden from view within the lateral fissure (see Figure 7.6). Primate primary auditory cortex comprises three adjacent areas (see Moerel, De Martino, & Formisano, 2014): Together these three areas are referred to as the *core region*. Surrounding the core region is a band—often called the *belt*—of areas of secondary auditory cortex. Areas of secondary auditory cortex outside the belt are called *parabelt areas* (Jasmin, Lima, & Scott, 2019). In total, there seem to be about 13 separate areas of auditory cortex in primates (see Brewer & Barton, 2016).

ORGANIZATION OF PRIMATE AUDITORY CORTEX. Three important principles of organization of primary auditory cortex have been identified. First, like the primary visual cortex, the primary auditory cortex is organized in functional columns (see Mizrahi, Shalev, & Nelken, 2014): All of the neurons encountered during a vertical microelectrode penetration of primary auditory cortex (i.e., a penetration at right angles to the cortical layers) tend to respond optimally to sounds in the same frequency range. Second, like the cochlea, auditory cortex has a tonotopic organization (see Jasmin, Lima, & Scott, 2019; Schreiner & Polley, 2014): Each area of auditory cortex appears to have a gradient of frequencies from low to high along its length. Third, auditory cortex is also organized according to the temporal components of sound; that is, variations in the amplitude of particular sound frequencies over time. For example, our auditory environments almost never consist of sounds that do not vary in their intensity over time. It seems that auditory cortex is sensitive to such fluctuations. This third organizing principle of auditory cortex is known as **periodotopy** (see Brewer & Barton, 2016).

WHAT SOUNDS SHOULD BE USED TO STUDY AUDITORY CORTEX? Why has research on auditory cortex lagged behind research on visual cortex? There are several reasons, but a major one is a lack of clear understanding of the dimensions along which auditory cortex evaluates

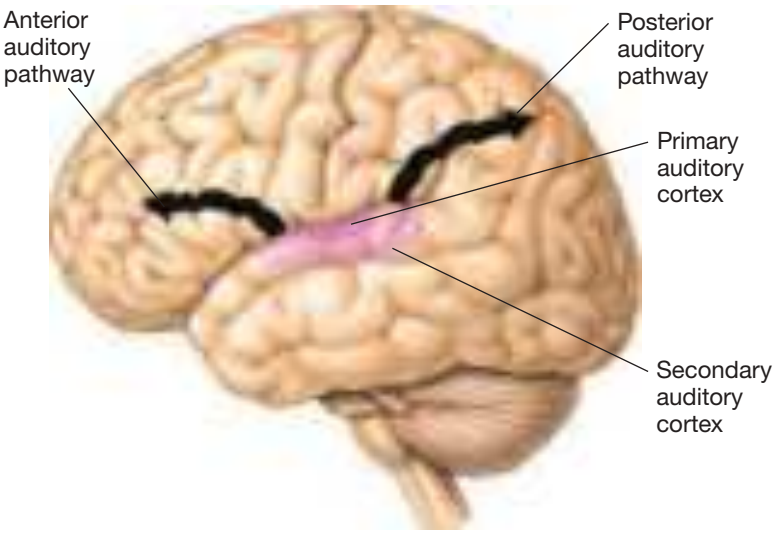
Figure 7.6 General location of the primary auditory cortex and areas of secondary auditory cortex. Most auditory cortex is hidden from view in the lateral fissure.



sound (Sharpee, Atencio, & Schreiner, 2011). You may recall that research on the visual cortex did not start to progress rapidly until it was discovered that most visual neurons respond to contrast. There is clear evidence of a hierarchical organization in auditory cortex—the neural responses of secondary auditory cortex tend to be more complex and varied than those of primary auditory cortex (see Jasmin, Lima, & Scott, 2019).

Many neurons in auditory cortex respond only weakly to simple stimuli such as pure tones, which have been widely employed in electrophysiological studies of auditory cortex. This practice is changing, however, partly in response to the discovery that natural sounds, in general, are better at eliciting responses from neurons in mammalian auditory cortex (see Gervain & Geffen, 2019; Kopp-Scheinpflug, Sinclair, & Linden, 2019).

Figure 7.7 The hypothesized anterior and posterior auditory pathways.



WHAT ANALYSES DOES THE AUDITORY CORTEX PERFORM? We now know that calculations by the auditory cortex produce signals that are not faithful representation of sounds (see Tsunada et al., 2016; Wang, 2018). More specifically, auditory cortex is now known to integrate information about the current perceptions and behaviors of an animal in order to produce auditory signals that are relevant to the animal's current situation (see Kuchibhotla & Bathellier, 2018; Lima, Krishnan, & Scott, 2016; Schneider & Mooney, 2018).

One example of an output signal from auditory cortex that is particularly relevant to an animal's current situation is the creation of representations of *auditory objects*. For example, it is believed that the auditory cortex can take the complex mixture of frequencies produced by a piano and convert it into a sound representation that allows us to say "That's the sound of a piano!" (see Angeloni & Geffen, 2018; Kuchibhotla & Bathellier, 2018; Tsunada et al., 2016).

TWO STREAMS OF AUDITORY CORTEX. Thinking about the general organization of auditory cortex has been inspired by research on visual cortex. Researchers have proposed that, just as there are two main cortical streams of visual analysis (dorsal and ventral), there are two main cortical streams of auditory analysis. Auditory signals are ultimately conducted to two large areas of association cortex: prefrontal cortex and posterior parietal cortex. There is good evidence that the *anterior auditory pathway* is more involved in identifying sounds (what), whereas the *posterior auditory pathway* is more involved in locating sounds (where)—see Jasmin, Lima, & Scott (2019) and van der Heijden et al. (2019). These pathways are illustrated in Figure 7.7.

AUDITORY–VISUAL INTERACTIONS. Sensory systems have traditionally been assumed to interact in association cortex. Indeed, as you have already learned, association cortex is usually defined as areas of cortex where such interactions, or associations, take place. Much of the research on sensory system interactions has focused on interactions between the auditory and visual systems, particularly on those that occur in the posterior parietal cortex (see Brang et al., 2013; Cohen, 2009). In one study of monkeys (Mullette-Gillman, Cohen, & Groh, 2005), some posterior parietal neurons were found to have visual receptive fields, some were found to have auditory receptive fields, and some were found to have both.

Functional brain imaging is widely used to investigate sensory system interactions. One advantage of functional brain imaging is that it does not focus on any one part of the brain; it records activity throughout the brain. Functional brain-imaging studies have confirmed that sensory interactions do occur in association cortex, but more importantly, they have repeatedly found evidence of sensory interactions at the lowest level of the sensory cortex hierarchy, in areas of primary sensory cortex (see Man et al., 2013; Smith & Goodale, 2015). This discovery is changing how we think about the interaction of sensory systems: Sensory system interaction is not merely tagged on after *unimodal* (involving one system) analyses are complete; sensory system interactions seem to be an early and integral part of sensory processing.

WHERE DOES THE PERCEPTION OF PITCH OCCUR? Recent research has answered one fundamental question about auditory cortex: Where does the perception of pitch likely occur? This seemed like a simple question to answer because most areas of auditory cortex have a clear tonotopic organization. However, when experimenters used sound stimuli in which frequency and pitch were

different—for example, by using the missing fundamental technique—most auditory neurons responded to changes in frequency rather than pitch. This information led Bendor and Wang (2005) to probe primary and secondary areas of monkey auditory cortex with microelectrodes to assess the responses of individual neurons to missing fundamental stimuli. They discovered one small area just anterior to primary auditory cortex that contained many neurons that responded to pitch rather than frequency, regardless of the quality of the sound. The same small area also contained neurons that responded to frequency, and Bendor and Wang suggested that this area was likely the place where frequencies of sound were converted to the perception of pitch. A comparable pitch area has been identified by fMRI studies in a similar location in the human brain.

Effects of Damage to the Auditory System

LO 7.7 Describe the effects of damage to the auditory system.

The study of damage to the auditory system is important for two reasons. First, it provides information about how the auditory system works. Second, it can serve as a source of information about the causes and treatment of clinical deafness.

AUDITORY CORTEX DAMAGE. Following bilateral lesions to the primary auditory cortex, there is often a complete loss of hearing, which presumably results from the shock of the lesion because hearing recovers in the ensuing weeks. The major permanent effects are loss of the ability to process the structural aspects of sounds—an ability that is necessary for the processing of speech sounds. Accordingly, patients with bilateral auditory cortex lesions are often said to be "word deaf" (see Jasmin, Lima, & Scott, 2019).

Consistent with the definitions of the two cortical auditory pathways, patients with damage to the anterior auditory cortex pathway (the *what pathway*) have trouble identifying sounds. Whereas, patients with damage to the posterior auditory cortex pathway (the *where pathway*) have difficulty localizing sounds (see Jasmin, Lima, & Scott, 2019).

DEAFNESS IN HUMANS. Deafness is one of the most prevalent human disabilities: An estimated 360 million people currently suffer from disabling hearing impairments (Lesica, 2018). Hearing impairment affects more than one's ability to detect sounds: it can lead to feelings of social isolation and has been associated with an increased risk for dementia (see Lesica, 2018; Peelle & Wingfield, 2016). Total deafness is rare, occurring in only 1 percent of hearing-impaired individuals.

Severe hearing problems typically result from damage to the inner ear or the middle ear or to the nerves leading from them rather than from more central damage. There are two common classes of hearing impairments: those associated with damage to the ossicles (*conductive deafness*) and those associated with damage to the cochlea or auditory nerve (*nerve deafness*). The major cause of nerve deafness is a loss of hair cell receptors (see Wallis, 2018; Wong & Ryan, 2015).

If only part of the cochlea is damaged, individuals may have nerve deafness for some frequencies but not others. For example, age-related hearing loss features a specific deficit in hearing high frequencies. That is why elderly people often have difficulty distinguishing "s," "f," and "t" sounds: They can hear people speaking to them but often have difficulty understanding what people are saying. Often, relatives and friends do not realize that much of the confusion displayed by the elderly stems from difficulty discriminating sounds (see Wingfield, Tun, & McCoy, 2005). Unfortunately, hearing aids often do not help with the processing of speech (see Lesica, 2018; Peelle & Wingfield, 2016).

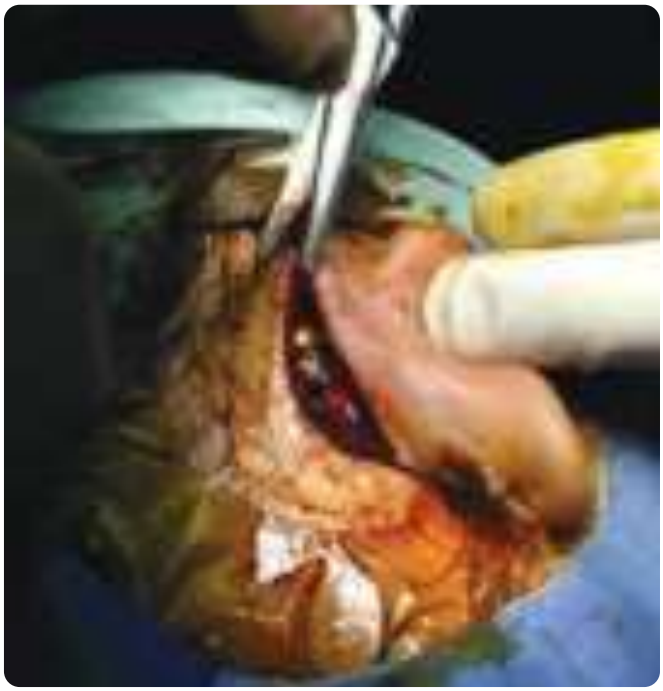
Hearing loss is sometimes associated with **tinnitus** (ringing of the ears). When only one ear is damaged, the ringing is perceived as coming from that ear; however, cutting the nerve from the ringing ear has no effect on the ringing. This suggests that neuroplastic changes to the auditory system resulting from deafness are the cause of tinnitus (see Eggermont & Tass, 2015; Elgoyhen et al., 2015; Shore, Roberts, & Langguth, 2016; Sedley et al., 2016).

Journal Prompt 7.1

Why do you think tinnitus is associated with deafness? [Hint: Sensory neurons don't stop firing in the absence of sensory input.]

Some people with nerve deafness benefit from cochlear implants (see Figure 7.8). *Cochlear implants* bypass damage to the auditory hair cells by converting sounds picked up by a microphone on the patient's ear to electrical signals, which are then carried into the cochlea by a bundle of electrodes. These signals excite the auditory nerve. Although cochlear implants can provide major benefits, they do not restore normal hearing. The sooner a person receives a cochlear implant after becoming deaf, the more likely they are to benefit, because disuse leads to alterations of the auditory neural pathways (see Kral & Sharma, 2012).

Figure 7.8 Cochlear implant: The surgical implantation is shown on the left, and a child with an implant is shown on the right.



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Scan Your Brain

Before we go on to discuss the other sensory systems, pause and scan your brain to check your knowledge of what you have learned in this chapter so far. Fill in the following blanks with the most appropriate terms. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your errors and omissions.

1. An area of the cortex that receives input from multiple sensory systems and integrates sensory information is called the _____ cortex.
2. Sensation is the process of detecting the presence of stimuli, and the higher-order process called _____ allows the interpretation of sensory patterns.
3. The simultaneous analysis of signals, also known as _____ processing, allows for information to flow through multiple pathways at the same time.
4. In the 1960s, the sensory organization was believed to be hierarchical, _____ _____, and serial.
5. The frequency of sound vibrations is linked to perceptions of _____.
6. Sound waves travel from the external environment to the outer ear, and through the auditory canal where they reach the _____ membrane.
7. The three smallest bones in the human body are the malleus, the incus, and the _____.
8. The _____ are auditory receptors located in the cochlea on the basilar membrane, and they increase firing in axons of the auditory nerve.
9. Axons from olivary neurons project to the _____ _____ via the lateral lemniscus.
10. The cochlea and the primary auditory cortex are both organized _____ on the bases of sound frequencies.
11. Damage to the ossicles is associated with _____ deafness, while damage to the cochlea is associated with _____ deafness.
12. The anterior auditory pathway is more involved in identifying sounds (what), whereas the _____ auditory pathway is more involved in locating sounds (where).

Scan Your Brain answers: (1) association, (2) perception, (3) parallel, (4) functionally homogeneous, (5) pitch, (6) tympanic, (7) stapes, (8) hair cells, (9) inferior colliculi, (10) tonotopically, (11) conductive, nerve, (12) posterior.

Somatosensory System: Touch and Pain

Sensations from your body are referred to as *somatosensations*. The system that mediates these bodily sensations—the *somatosensory system*—is composed of three separate but interacting systems: (1) an *exteroceptive system*, which senses external stimuli that are applied to the skin; (2) a *proprioceptive system*, which monitors information about the position of the body that comes from receptors in the muscles, joints, and organs of balance; and (3) an *interoceptive system*, which provides general information about conditions within the body (e.g., temperature and blood pressure). This module deals almost exclusively with the exteroceptive system, which itself comprises three somewhat distinct divisions: a division for perceiving *mechanical stimuli* (touch), one for *thermal stimuli* (temperature), and one for *nociceptive stimuli* (pain).

Cutaneous Receptors

LO 7.8 **Name some of the cutaneous receptors and explain the functional significance of fast versus slow receptor adaptation.**

There are many kinds of receptors in the skin (see Owens & Lumpkin, 2014; Zimmerman, Bai, & Ginty, 2014). Figure 7.9 illustrates four of them. The simplest cutaneous receptors are the *free nerve endings* (neuron endings with no specialized structures on them), which are particularly sensitive to temperature change and pain. The largest and deepest cutaneous receptors are the onion-like *Pacinian corpuscles*; because they adapt rapidly, they respond to sudden displacements of the skin but not to constant pressure. In contrast, *Merkel's disks* and *Ruffini endings* both adapt slowly and respond to gradual skin indentation and skin stretch, respectively.

To appreciate the functional significance of fast and slow receptor adaptation, consider what happens when a constant pressure is applied to the skin. The pressure evokes a burst of firing in all receptors, which corresponds to the sensation of being touched; however, after a few hundred milliseconds, only the slowly adapting receptors remain active, and the quality of the sensation changes. In fact, you are often totally unaware of constant skin pressure; for example, you are usually unaware of the feeling of your clothes against your body until you focus attention on it. As a consequence, when you try to engage in **stereognosis** (identifying objects by touch), you manipulate the object in your hands so that the pattern of stimulation continually changes. Having some receptors that adapt quickly and some that adapt slowly provides information about both the dynamic and static qualities of tactual stimuli.

The structure and physiology of each type of somatosensory receptor seem to be specialized for a different function. However, in general, the various receptors tend to function in the same way: Stimuli applied to the skin deform or change the chemistry of the receptor, and this in turn changes the permeability of the receptor cell membrane to various ions (see Delmas, Hao, & Rodat-Despoix, 2011). The result is a neural signal.

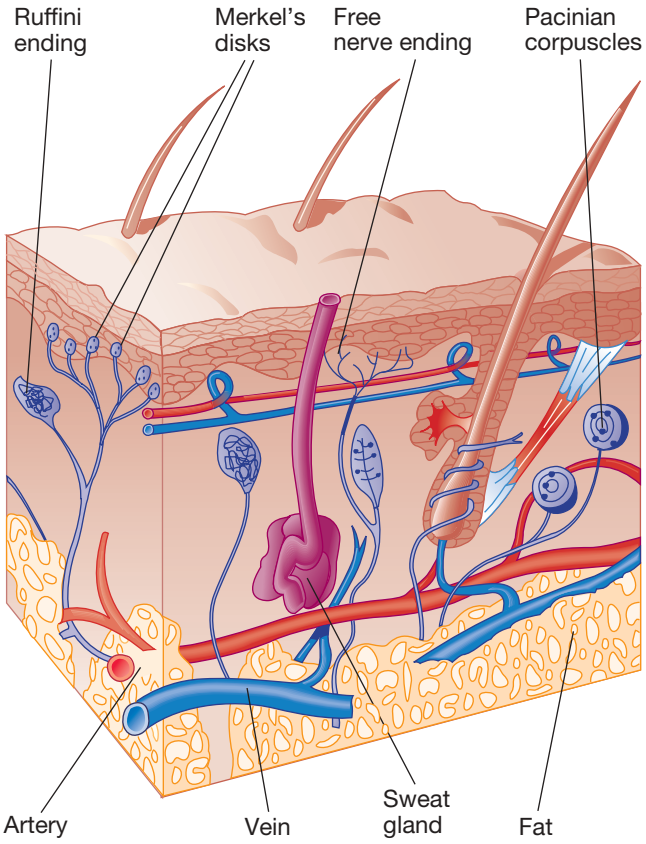


Figure 7.9 Four cutaneous receptors that occur in human skin.

Initially, it was assumed that each type of receptor located in the skin (see Figure 7.9) mediates a different tactile sensation (e.g., touch, pain, heat), but this has not proven to be the case. Each tactile sensation appears to be produced by the interaction of multiple receptor mechanisms, and each receptor mechanism appears to contribute to multiple sensations (see Hollins, 2010; Lumpkin & Caterina, 2007; McGlone & Reilly, 2010). In addition, skin cells that surround particular receptors also seem to play a role in the quality of the sensations produced by that receptor (see Zimmerman, Bai, & Ginty, 2014). Indeed, new forms of tactile sensation are still being discovered (see McGlone, Wessberg, & Olausson, 2014; Ran, Hoon, & Chen, 2016).

Two Major Somatosensory Pathways

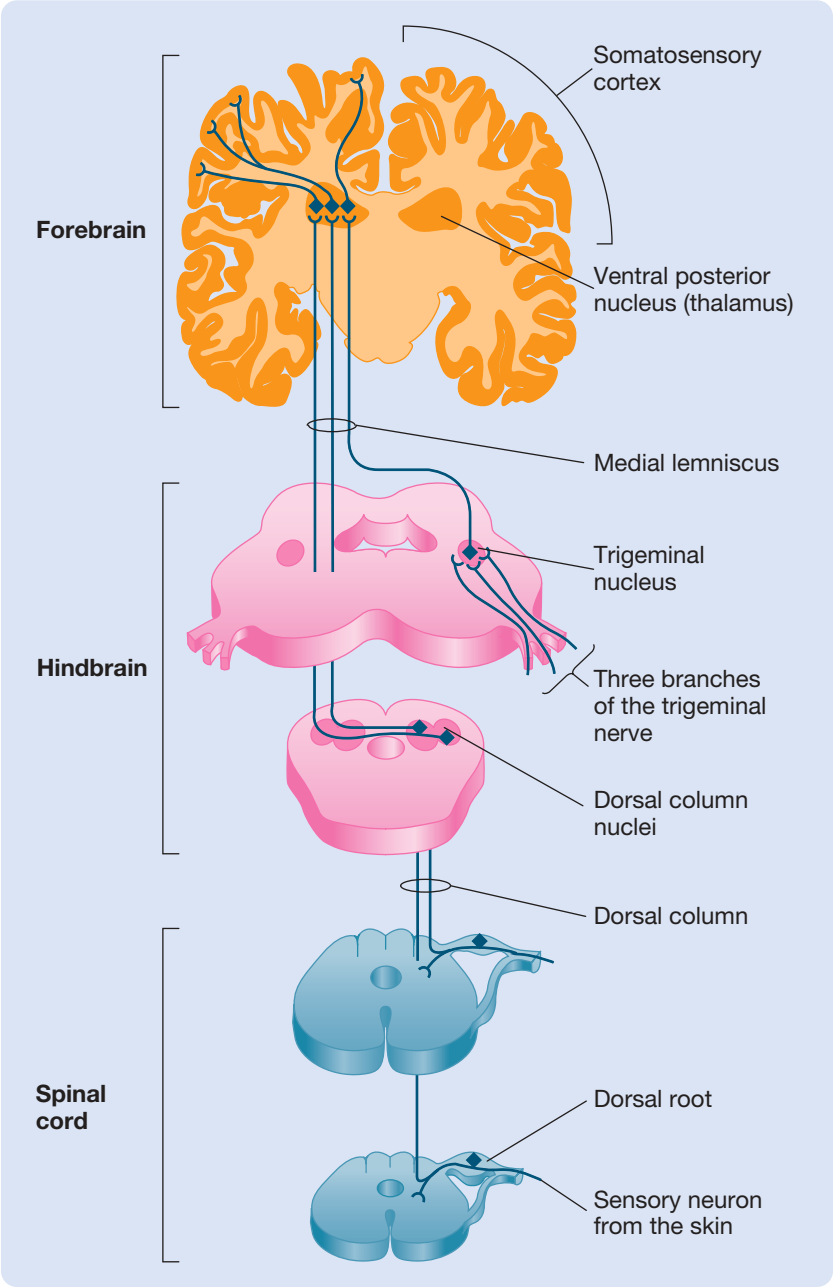
LO 7.9 **Describe the two major somatosensory pathways.**

Somatosensory information ascends from each side of the body to the human cortex over several pathways, but there

are two major ones: the dorsal-column medial-lemniscus system and the anterolateral system. The **dorsal-column medial-lemniscus system** tends to carry information about touch and proprioception, and the **anterolateral system** tends to carry information about pain and temperature (see Ran et al., 2016). The key words in the preceding sentence are "tends to": The separation of function in the two pathways is far from complete. Accordingly, lesions of the dorsal-column medial-lemniscus system do not eliminate touch perception or proprioception, and lesions of the anterolateral system do not eliminate perception of pain or temperature.

The dorsal-column medial-lemniscus system is illustrated in Figure 7.10. The sensory neurons of this system enter the spinal cord via a dorsal root, ascend ipsilaterally in the **dorsal columns**, and synapse in the *dorsal column nuclei* of the medulla. The axons of dorsal column nuclei neurons *decussate* (cross over to the other side of the brain) and then ascend in the **medial lemniscus** to the contralateral **ventral posterior nucleus** of the thalamus. The ventral posterior nuclei also receive input via the three branches of the trigeminal nerve, which carry somatosensory information from the contralateral areas of the face. Most neurons of the ventral posterior nucleus project to the *primary somatosensory cortex* (*SI*); others project to the *secondary somatosensory cortex* (*SII*) or the posterior parietal cortex. Neuroscience trivia buffs will almost certainly want to add to their collection the fact that the dorsal column neurons that originate in the toes are the longest neurons in the human body.

Figure 7.10 The dorsal-column medial-lemniscus system. The pathways from only one side of the body are shown.



The anterolateral system is illustrated in Figure 7.11. Most dorsal root neurons of the anterolateral system synapse as soon as they enter the spinal cord. The axons of most of the second-order neurons decussate but then ascend to the brain in the contralateral anterolateral portion of the spinal cord; however, some do not decussate but ascend ipsilaterally. The anterolateral system comprises three different tracts: the *spinothalamic tract*, the *spinoreticular tract*, and the *spinotectal tract*. The three branches of the trigeminal nerve carry pain and temperature information from the face to the same thalamic sites. The pain and temperature information that reaches the thalamus is then distributed to somatosensory cortex and other parts of the brain.

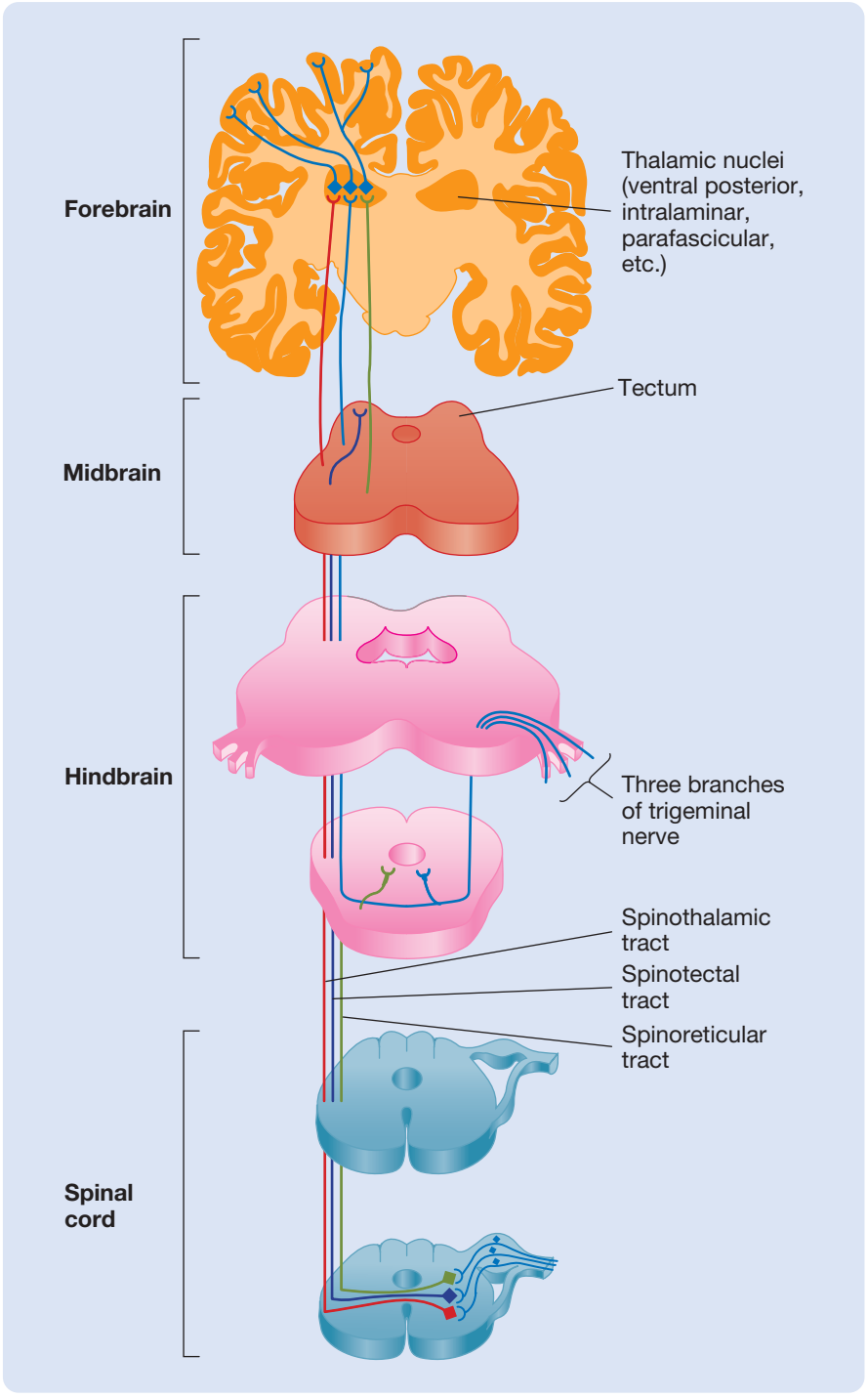
If both ascending somatosensory paths are completely transected by a spinal injury, the patient can feel no body sensation from below the level of the cut. Clearly, when it comes to spinal injuries, lower is better.

Cortical Areas of Somatosensation

LO 7.10 **Describe the cortical somatosensory areas and their somatotopic layout.**

In 1937, Penfield and his colleagues mapped the primary somatosensory cortex of patients during neurosurgery (see Figure 7.12). Penfield applied electrical stimulation to various sites on the cortical

Figure 7.11 The anterolateral system. The pathways from only one side of the body are shown.



surface, and the patients, who were fully conscious under a local anesthetic, described what they felt. When stimulation was applied to the *postcentral gyrus*, the patients reported somatosensory sensations in various parts of their bodies. When Penfield mapped the relation between each site of stimulation and the part of the body in which the sensation was felt, he discovered that the human primary somatosensory cortex (SI) is **somatotopic**—organized according to a map of the body surface (see Chen et al., 2015). This somatotopic map is commonly referred to as the **somatosensory homunculus** (*homunculus* means "little man").

Notice in Figure 7.12 that the somatosensory homunculus is distorted; the greatest proportion of SI is dedicated to receiving input from the parts of the body we use to make tactile discriminations (e.g., hands, lips, and tongue). In contrast, only small areas of SI receive input from large areas of the body, such as the back, that are not usually used to make somatosensory discriminations. The Check It Out demonstration on page 197 allows you to experience the impact this organization has on your ability to perceive touches.

A second somatotopically organized area, SII, lies just ventral to SI in the postcentral gyrus, and much of it extends into the lateral fissure. SII receives most of its input from SI and is thus regarded as secondary somatosensory cortex. In contrast to SI, whose input is largely contralateral, SII receives substantial input from both sides of the body. Much of the output of SI and SII goes to the association cortex of the *posterior parietal lobe* (see McGlone & Reilly, 2010).

Studies of the responses of single neurons in primary somatosensory cortex found evidence for columnar organization—similar to that in visual and auditory cortex. Each neuron in a particular column of primary somatosensory cortex had a receptive field on the same part of the body and responded most robustly to the same type of tactile stimuli (e.g., light touch or heat). Moreover, single-neuron recordings suggested that primary somatosensory-cortex is composed of four functional strips, each with a similar, but separate, somatotopic organization. Each strip of primary somatosensory cortex is most sensitive to a different kind of somatosensory input (e.g., to light touch or pressure). Thus, if one were to record from neurons across the four strips, one would find neurons that "preferred" four different kinds of tactile stimulation, all to the same part of the body.

Reminiscent of the developments in the study of visual and auditory cortex, it has been proposed that two streams of analysis proceed from SI: a dorsal stream that projects to posterior parietal cortex and participates in multisensory

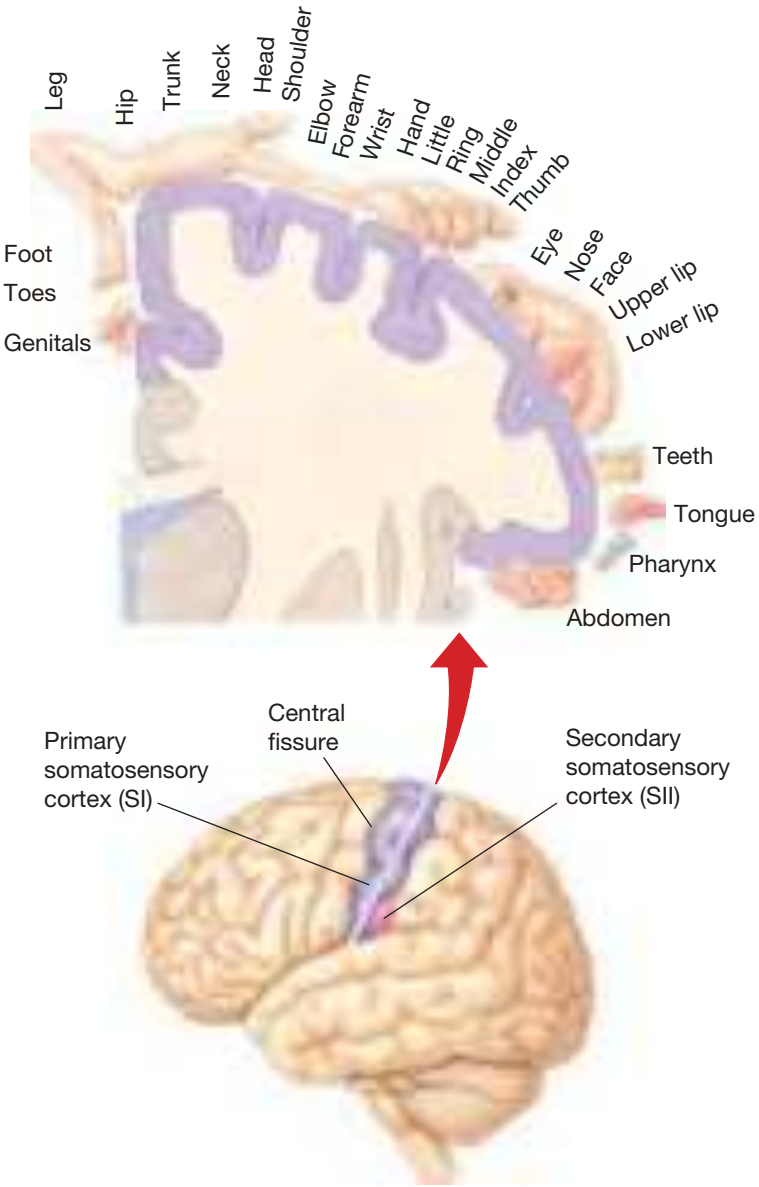


Figure 7.12 The locations of human primary somatosensory cortex (SI) and one area of secondary somatosensory cortex (SII) with the conventional portrayal of the somatosensory homunculus. Something has always confused us about this portrayal of the somatosensory homunculus: The body is upside down, while the face is right side up. It now appears that this conventional portrayal is wrong. The results of an fMRI study suggest that the face representation is also inverted. (Based on Servos et al., 1999.)

Based on Servos, P., Engel, S. A., Gati, J., & Menon, R. (1999). fMRI evidence for an inverted face representation in human somatosensory cortex. *Neuroreport*, *10*(7), 1393–1395.

Check It Out

Touching a Back

Because only a small portion of human primary somatosensory cortex receives input from the entire back, people have difficulty recognizing objects that touch their backs. You may not have noticed this tactile deficiency—unless, of course, you often try to identify objects by feeling them with your back. You will need one thing to demonstrate the recognition deficiencies of the human back: a friend. Touch your friend on the back with one, two, or three fingers, and ask your friend how many fingers he or she feels. When using two or three fingers, be sure they touch the back simultaneously because temporal cues invalidate this test of tactile discrimination. Repeat the test many times, adjusting the distance between the touches on each trial. Record the results. What you should begin to notice is that the back is incapable of discriminating between separate touches unless the distance between the touches is considerable. In contrast, fingertips can distinguish the number of simultaneous touches even when the touches are very close.

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integration and direction of attention, and a ventral stream that projects to SII and participates in the perception of objects' shapes (Yau, Connor, & Hsiao, 2013).

EFFECTS OF DAMAGE TO THE PRIMARY SOMATOSENSORY CORTEX. The effects of damage to the primary somatosensory cortex are often remarkably mild—presumably because the somatosensory system features numerous parallel pathways. Corkin, Milner, and Rasmussen (1970) assessed the somatosensory abilities of patients with epilepsy before and after a unilateral excision that included SI. Following the surgery, the patients displayed two minor contralateral deficits: a reduced ability to detect light touch and a reduced ability to identify objects by touch (i.e., a deficit in stereognosis). These deficits were bilateral only in those cases in which the unilateral lesion encroached on SII.

Somatosensory System and Association Cortex

LO 7.11 Name the areas of association cortex that somatosensory signals are sent to, and describe the functional properties of one of those areas.

Somatosensory signals are ultimately conducted to the highest level of the sensory hierarchy, to areas of association cortex in prefrontal and posterior parietal cortex.

Posterior parietal cortex contains *bimodal neurons* (neurons that respond to activation of two different sensory systems); some of these respond to both somatosensory and visual stimuli. The visual and somatosensory receptive fields of each neuron are spatially related; for example, if a neuron has a somatosensory receptive field centered in the left hand, its visual field is adjacent to the left hand (see Crochet, Lee, & Peterson, 2019). Remarkably, as the left hand moves, the visual receptive field of the neuron moves with it. The existence of these bimodal neurons motivated the following interesting case study by Schendel and Robertson (2004).

The Case of W.M., Who Reduced His Scotoma with His Hand

W.M. suffered a stroke in his right posterior cerebral artery. The stroke affected a large area of his right occipital and parietal lobes and left him with severe left *hemianopsia* (a condition in which a scotoma covers half the visual field). When tested with his left hand in his lap, W.M. detected 97.8 percent of the stimuli presented in his right visual field and only 13.6 percent of those presented in his left visual field. However, when he was tested with his left hand extended into his left visual field, his ability to detect stimuli in his left visual field improved significantly. Further analysis showed that this general improvement resulted from W.M.'s greatly improved ability to see those objects in the left visual field that were near his left hand. Remarkably, this area of improved performance around his left hand was expanded even further when he held a tennis racket in his extended left hand.

Somatosensory Agnosias

LO 7.12 Describe the two major types of somatosensory agnosia.

There are two major types of somatosensory agnosia. One is **astereognosia**—the inability to recognize objects by touch. Cases of pure astereognosia—those that occur in the absence of simple sensory deficits—are rare (Corkin, Milner, & Rasmussen, 1970). The other type of somatosensory agnosia is **asomatognosia**—the failure to recognize parts of one's own body. Asomatognosia is usually unilateral, affecting only the left side of the body, and it is usually associated with extensive damage to the right temporal and posterior parietal lobe (Feinberg et al., 2010). The case of Aunt Betty (Klawans, 1990) is an example.

The Case of Aunt Betty, Who Lost Half of Her Body*

Aunt Betty was my patient. She wasn't really my aunt, she was my mother's best friend.

As we walked to her hospital room, one of the medical students described the case. "Left hemiplegia [left-side paralysis], following a right-hemisphere stroke." I was told.

Aunt Betty was lying on her back with her head and eyes turned to the right. "Betty," I called out.

I approached her bed from the left, but Aunt Betty did not turn her head or even her eyes to look toward me.

"Hal," she called out. "Where are you?"

I turned her head gently toward me, and we talked. It was clear that she had no speech problems, no memory loss, and no confusion. She was as sharp as ever. But her eyes still looked to the right, as if the left side of her world did not exist.

I held her right hand in front of her eyes. "What's this?" I asked.

"My hand, of course," she said with an intonation that suggested what she thought of my question.

"Well then, what's this?" I said, as I held up her limp left hand where she could see it.

"A hand."

"Whose hand?"

"Your hand, I guess," she replied. She seemed puzzled. I placed her hand back on the bed.

"Why have you come to the hospital?" I asked.

"To see you," she replied hesitantly. I could tell that she didn't know why.

Aunt Betty was in trouble.

As in the case of Aunt Betty, asomatognosia is often accompanied by **anosognosia**—the failure of neuropsychological patients to recognize their own symptoms. Indeed, anosognosia is a common, but curious, symptom of many neurological disorders—many neurological patients with severe behavioral problems think that they are doing quite well.

Asomatognosia is commonly a component of **contralateral neglect**—the tendency not to respond to stimuli that are contralateral to a right-hemisphere injury. You will learn more about contralateral neglect in Chapter 8.

*Based on *Newton's Madness* by Harold Klawans (Harper & Row 1990).

Rubber-Hand Illusion

LO 7.13 Describe the rubber-hand illusion and its neural mechanisms.

We perceive ownership of our own body parts. Somesthetic sensation is so fundamental that it is taken for granted. This is why exceptions to it, such as asomatognosia, are so remarkable. In the past decade, another exception—one that is in some respects the opposite of asomatognosia—has been a focus of research. This exception is the **rubber-hand illusion** (the feeling that an extraneous object, in this case a rubber hand, is actually part of one's own body).

The rubber-hand illusion can be generated in a variety of ways, but it is usually induced in the following manner (see Kilteni et al., 2015; Moseley, Gallace, & Spence, 2012). A healthy volunteer's hand is hidden from view by a screen, and a rubber hand is placed next to the hidden hand but in clear sight. Then the experimenter repeatedly strokes the hidden hand and the rubber hand synchronously—see Figure 7.13. In less than a minute, many volunteers begin to feel that the rubber hand is part of their own body (see Blanke, Slater, & Serino, 2015). Interestingly, when this happens, the temperature in the hidden hand drops (Moseley et al., 2008).

Although the neural mechanisms for the rubber-hand illusion are unknown, functional imaging studies have suggested that association cortex in the posterior parietal and frontal lobes plays a role in its induction (Limanowski & Blankenburg, 2015; Tsakiris et al., 2007). It has been suggested that those frontal and parietal-*bimodal neurons* with both visual and somatosensory fields play a critical role (Kilteni et al., 2015). Interestingly, the rubber-hand illusion is not limited to humans: rubber tails have been demonstrated in mice and rubber arms in monkeys (see Brecht et al., 2017).

Figure 7.13 One common induction method for the rubber-hand illusion. The participant's hand is hidden from view by a screen, and a rubber hand is placed next to their hidden hand but in clear sight. Then the experimenter repeatedly strokes the hidden hand and the rubber hand synchronously.

Perception of Pain

LO 7.14 Explain why the perception of pain is said to be paradoxical.

A paradox is a logical contradiction. The perception of pain is paradoxical in three important respects, which are explained in the following three subsections.

PAIN IS ADAPTIVE. One paradox of pain is that an experience that seems in every respect to be so bad is in fact extremely important for our survival. There is no special stimulus for pain; it is a response to potentially harmful stimulation of any type. It warns us to stop engaging in potentially harmful activities or to seek treatment (see Navratilova & Porreca, 2014).

The value of pain is best illustrated by the cases of people, like Miss C., who experience no pain (Melzack & Wall, 1982).

The Case of Miss C., the Woman Who Felt No Pain

Miss C., a university student, was very intelligent, and she was normal in every way except that she never felt pain. (Her condition is now referred to as *congenital insensitivity to pain*.)

She felt no pain when subjected to strong electric shock, burning hot water, or an ice bath. Equally astonishing was the fact that she showed no changes in blood pressure, heart rate, or respiration when these stimuli were presented. Furthermore, she did not sneeze, cough, or display corneal reflexes (blinking to protect the eyes). As a child, she had bitten off the tip of her tongue while chewing food and had suffered severe burns after kneeling on a radiator.

Miss C. exhibited pathological changes in her knees, hip, and spine because of the lack of protection to joints provided by pain sensation. She apparently failed to shift her weight when standing, to turn over in her sleep, or to avoid harmful postures.

Miss C. died at the age of 29 of massive infections and extensive skin and bone trauma.

Journal Prompt 7.2

Cases of congenital insensitivity to pain illustrate something important about the adaptive value of pain. Based on this case study, can you specify what that adaptive value might be?

Cox and colleagues (2006) studied six cases of congenital insensitivity to pain among members of a family from Pakistan. They were able to identify the genetic abnormality underlying the disorder in these six individuals: a gene that influences the synthesis of sodium ion channels. Indeed, knockout mice that are missing this sodium ion channel gene show a comparable indifference to pain (Gingras et al., 2014).

PAIN HAS NO CLEAR CORTICAL REPRESENTATION. The second paradox of pain is that it has no obvious cortical representation (Rainville, 2002). Painful stimuli activate many areas of cortex including the thalamus, SI and SII, the insula, and the anterior cingulate cortex (see Figure 7.14)—see Navratilova and Porreca (2014). However, none of those areas seems necessary for the perception of pain. For example, painful stimuli usually elicit responses in SI and SII (see Zhuo, 2008). However, removal of SI and SII in humans is not associated with any change in the threshold for pain. Indeed, *hemispherectomized* patients (those with one cerebral hemisphere removed) can still perceive pain from both sides of their bodies.

The cortical area that has been most frequently linked to pain is the **anterior cingulate cortex** (see Figure 7.14). For example, Craig et al. (1996) examined the effect of the **thermal grid illusion:** the perception of pain that results from placing one's hand on a grid of metal rods that alternate between cool and warm (see Figure 7.15; Bokiniec et al., 2018). When participants experienced such illusory pain while undergoing fMRI, only the anterior cingulate cortex displayed a marked increase in activity (Craig et al., 1996).

PAIN IS MODULATED BY COGNITION AND EMOTION. The third paradox of pain is that this most compelling of all sensory experiences can be so effectively suppressed by cognitive and emotional factors (see Bushnell, Čeko, & Low, 2013; Senkowski, Höfle, & Engel, 2014). For example, males participating in a certain religious ceremony suspend objects from hooks embedded in their backs with little evidence of pain (see also Figure 7.16); severe wounds suffered by soldiers in battle are often associated with little pain; and people injured in life-threatening situations frequently feel no pain until the threat is over.

Three discoveries led to the identification of a descending pain-control circuit. First was the discovery that electrical stimulation of the **periaqueductal gray (PAG)** has analgesic (pain-blocking) effects: Reynolds (1969) was able to perform surgery on rats with no analgesia other than that provided by PAG stimulation. Second was the discovery that the PAG and other areas of the brain contain specialized receptors for opioid analgesic drugs such as morphine. And third was the isolation of several endogenous (internally produced) opioid analgesics, the **endorphins**, which you learned about in Chapter 4. These three findings together suggested that analgesic drugs and psychological factors might block pain through an endorphin-sensitive circuit that descends from the PAG.

Figure 7.14 Location of the anterior cingulate cortex in the cingulate gyrus.

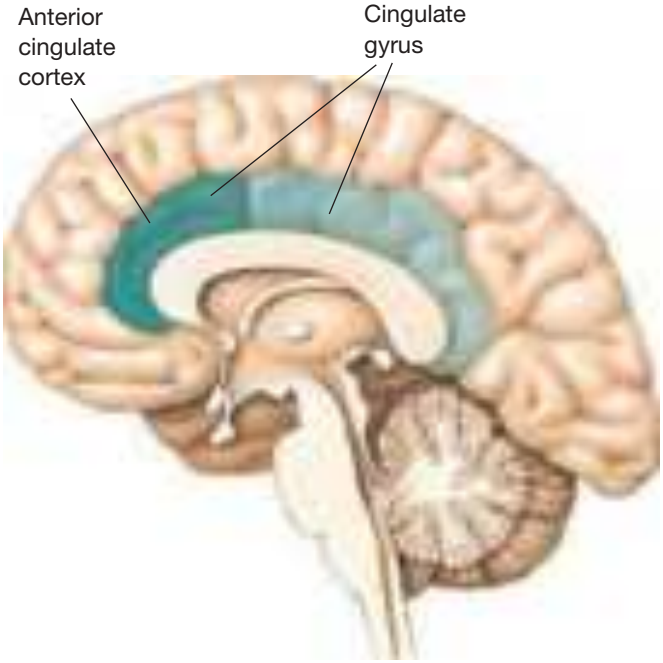


Figure 7.15 The thermal grid illusion. Pain is perceived when one's hand is placed on a grid of metal rods that alternate between cool and warm.

Figure 7.16 When experienced as part of a ritual, normally excruciating conditions (e.g., walking on hot coals) often produce little pain.

VanVang/Alamy Stock Photo

just the opposite is true (see Luo, Kuner, & Kuner, 2014). **Neuropathic pain** is severe chronic pain in the absence of a recognizable pain stimulus. A typical case of neuropathic pain develops after an injury: Once the injury heals, there seems to be no reason for further pain, but the patient experiences chronic excruciating pain. In many cases, attacks of neuropathic pain can be triggered by an innocuous stimulus, such as a gentle touch.

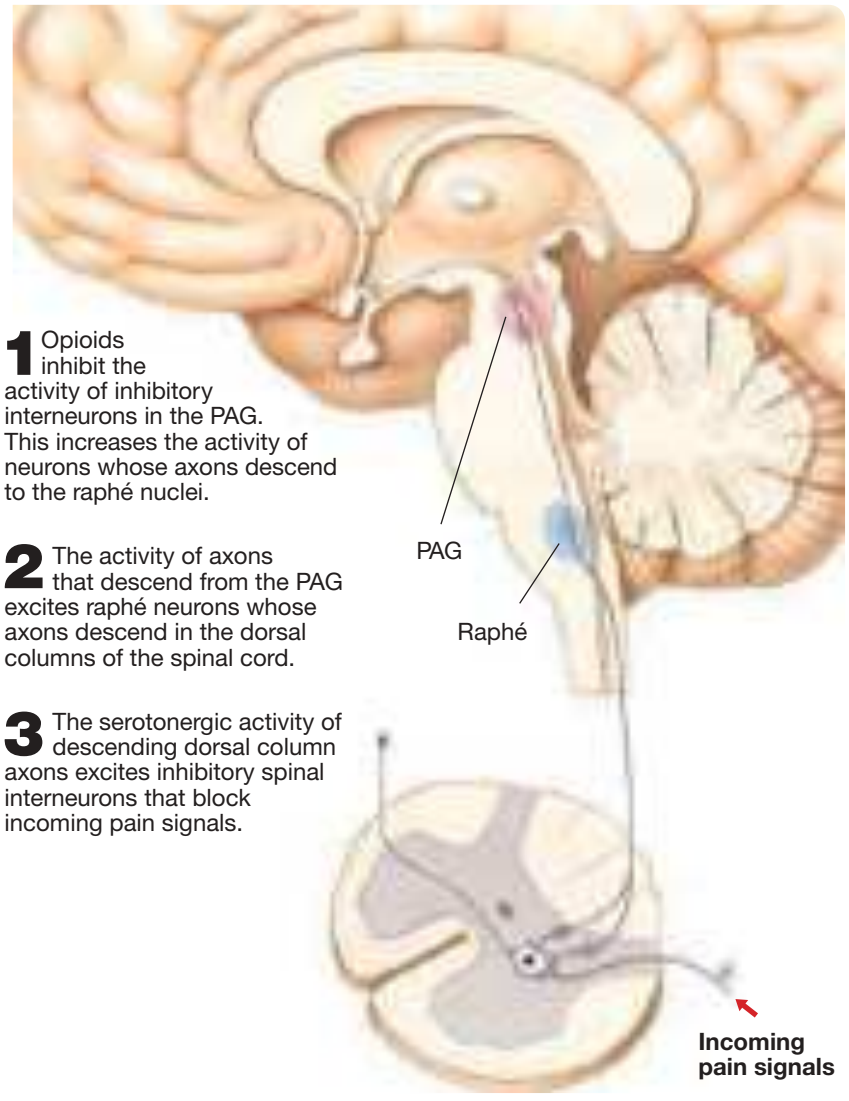
Although neuropathic pain may be perceived to be in a limb—even in an amputated limb (see Chapter 10)—it is caused by abnormal activity in the CNS. Thus, cutting nerves from the perceived location of the pain often brings little or no comfort. And, unfortunately, medications that have been developed to treat the pain associated with injury are usually ineffective against neuropathic pain.

There are three promising lines of research into the neural mechanisms of neuropathic pain. First, recent research has implicated aberrant microglial activity in neuropathic

Figure 7.17 illustrates the descending analgesia circuit first hypothesized by Basbaum and Fields (1978). They proposed that the output of the PAG excites the serotonergic neurons of the *raphé nuclei* (a cluster of serotonergic nuclei in the core of the medulla), which in turn project down the dorsal columns of the spinal cord and excite interneurons that block incoming pain signals in the dorsal horn.

Descending analgesia pathways have been the subject of intensive investigation since the first model was proposed by Basbaum and Fields in 1978. In order to incorporate the mass of accumulated data, models of the descending analgesia circuits have grown much more complex (see Lau & Vaughan, 2014). For example, both the anterior cingulate cortex and prefrontal cortex are now believed to be important components of descending analgesia circuits (see Davis et al., 2017).

Figure 7.17 Basbaum and Fields's (1978) model of the descending analgesia circuit.



Neuropathic Pain

LO 7.15 Define neuropathic pain and describe some of its putative neural mechanisms.

In most cases, plasticity of the human nervous system helps it function more effectively. In the case of neuropathic pain,

pain, including the induction of neuroplastic changes that lead to the persistence of pain long after the injury has healed (see Inoue & Tsuda, 2018; Kuner & Flor, 2017). Second, there is considerable evidence supporting the involvement of *epigenetic mechanisms* (see Chapter 2) in neuropathic pain (see Birklein et al., 2018; Zhang et al., 2016). Drugs are currently being developed to modify such epigenetic changes in order to treat neuropathic pain (see Neiderberger et al., 2017). Third, the aforementioned neuroplastic and epigenetic changes are most prominent in the anterior cingulate cortex (Bliss et al., 2016; Zhuo, 2016) and prefrontal cortex (see Peng et al., 2017)—structures that are both involved in descending analgesia pathways (see Davis et al., 2017).

Chemical Senses: Smell and Taste

Olfaction (smell) and *gustation* (taste) are referred to as the chemical senses because their function is to monitor the chemical content of the environment. Smell is the response of the olfactory system to airborne chemicals that are drawn by inhalation over receptors in the nasal passages, and taste is the response of the gustatory system to chemicals in solution in the oral cavity.

Adaptive Roles of the Chemical Senses

LO 7.16 Describe two adaptive roles for the chemical senses.

When we are eating, smell and taste act in concert. Molecules of food excite both smell and taste receptors and produce an integrated sensory impression termed **flavor**. The contribution of olfaction to flavor is often underestimated, but you won't make this mistake if you remember that people with no sense of smell have difficulty distinguishing the flavors of apples and onions. Flavor is also influenced by a number of other factors such as the temperature, texture, and appearance of the food and a person's level of satiety (see Chaudhauri & Roper, 2010; Rolls et al., 2010).

In humans, the main adaptive role of the chemical senses is the evaluation of potential foods (i.e., encouraging the consumption of sources of energy and nutrients while avoiding toxins) in natural environments, where potential foods do not come with labels (see Yarmolinsky, Zuker, & Ryba, 2009). However, in many other species, the chemical senses also play a major role in regulating social interactions. The members of many species release **pheromones**—chemicals that influence the physiology and behavior of *conspecifics* (members of the same species)—see Stowers and Kuo (2015); Leighton and Sternberg (2016). For example, Murphy and Schneider (1970) showed that the sexual and aggressive behavior of hamsters is under pheromonal control. Normal male hamsters attack and kill unfamiliar males that are placed in their colonies, whereas they mount and impregnate unfamiliar sexually receptive females. However, male hamsters that are unable to smell the intruders engage in neither aggressive nor sexual behavior. Murphy and Schneider confirmed the olfactory basis of hamsters' aggressive and sexual behavior in a particularly devious fashion. They swabbed a male intruder with the vaginal secretions of a sexually receptive female before placing it in an unfamiliar colony; in so doing, they converted it from an object of hamster assassination to an object of hamster lust.

The possibility that humans may release sexual pheromones has received considerable attention because of its financial and recreational potential. However, there is little evidence that humans release or respond to sexual pheromones (see Wyatt, 2017).

Olfactory System

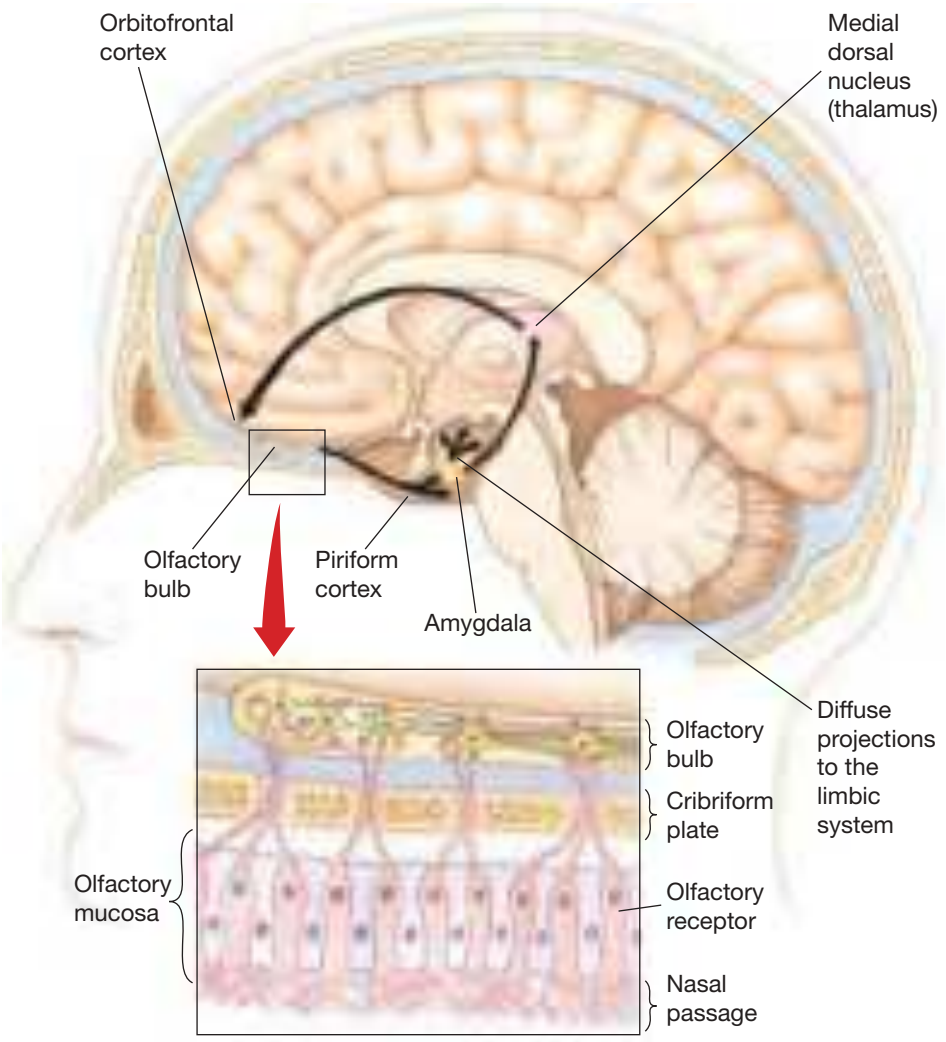
LO 7.17 Describe the olfactory system.

The olfactory system is illustrated in Figure 7.18. The olfactory receptor cells are located in the upper part of the nose, embedded in a layer of mucus-covered tissue called the **olfactory mucosa**. Their dendrites are located in the nasal passages, and their axons pass through a porous portion of the skull (the *cribriform plate*) and enter the **olfactory bulbs**, where they synapse on neurons that project via the *olfactory* tracts to the brain.

For decades, it was assumed that there were only a few types of olfactory receptors. Different profiles of activity in a small number of receptor types were thought to lead to the perception of various smells—in the same way that the profiles of activity in three types of cones were once thought to lead to the perception of colors. Then, at the turn of the 21st century, it was discovered that rats and mice have about 1,000 different kinds of olfactory receptor proteins and that humans have about 300 (see Grabska-Barwińska et al., 2017; Uchida, Poo, & Haddad, 2014).

In mammals, each olfactory receptor cell contains only one type of receptor protein molecule (see Giesel & Datta, 2014; Uchida, Poo, & Haddad, 2014). Olfactory receptor proteins are in the membranes of the dendrites of the olfactory receptor cells, where they can be stimulated by circulating airborne chemicals in the nasal passages. Researchers have attempted to discover the functional principle by which the various receptors are distributed through the olfactory mucosa. If there is such a principle, it has not yet been discovered: All types of olfactory receptors appear to be scattered throughout the mucosa, providing no clue about the organization of the system. Because each type of olfactory receptor responds in varying degrees to a wide variety of

Figure 7.18 The human olfactory system.



odors, each odor seems to be encoded by component processing—that is, by the pattern of activity across different receptor types (see Giesel & Datta, 2014).

The axons of olfactory receptors terminate in discrete clusters of neurons that lie near the surface of the olfactory bulbs—these clusters are called the **olfactory glomeruli**. Each glomerulus receives input from several thousand olfactory receptor cells, all with the same receptor protein (see Gupta, Albeanu, & Bhalla, 2015; Wanner et al., 2016; Tian et al., 2016). In mice, there are one or two glomeruli in each olfactory bulb for each receptor protein type (see Schoppa, 2009).

Because systematic topographic organization is apparent in other sensory systems (e.g., *retinotopic* and *tonotopic* layouts), researchers have been trying to discover whether glomeruli sensitive to particular odors are arrayed systematically on the surfaces of the olfactory bulbs. Indeed, three lines of evidence indicate that there is a systematic layout (see Cheetham & Belluscio, 2014; Tsai & Barnea, 2014):

- There is mirror symmetry between the left and right olfactory bulbs—glomeruli sensitive to particular odors tend to be located at the same sites on the two bulbs.
- The glomeruli sensitive to particular odors are arrayed on the olfactory bulbs in the same way in different members of the same species.
- The layout of the glomeruli is similar in related species (i.e., rats and mice).

Although it is clear that the olfactory bulbs are organized topographically and that the layout is not random (see Wanner et al., 2016), the topographic principle according to which the glomeruli are arrayed has yet to be discovered (see Murthy, 2011). The poorly understood topographic organization of the olfactory bulbs has been termed a **chemotopic** map (see Falasconi et al., 2012).

New olfactory receptor cells are created throughout each individual's life to replace those that have deteriorated. Once created, the new receptor cells develop axons, which grow until they reach the appropriate target sites in the olfactory bulb. Each new olfactory receptor cell survives only a few weeks before being replaced. How the axons from newly formed receptors scattered about the nasal mucosa find their target glomeruli in the olfactory bulb remains a mystery (see Mori & Sakano, 2011).

Each olfactory bulb projects axons to several structures of the medial temporal lobes, including the amygdala and the **piriform cortex**—an area of medial temporal cortex adjacent to the amygdala (see Bekkers & Suzuki, 2013). The piriform cortex is considered to be primary olfactory cortex, but this designation is somewhat arbitrary (see Gottfried, 2010). The olfactory system is the only sensory system whose major sensory pathway reaches the cerebral cortex without first passing through the thalamus.

Two major olfactory pathways leave the amygdala-piriform area. One projects diffusely to the limbic system, and the other projects via the **medial dorsal nuclei** of the thalamus to the **orbitofrontal cortex**—the area of cortex on the inferior surface of the frontal lobes next to the *orbits* (eye sockets)—see Mainland et al. (2014). The limbic pathway

is thought to mediate the emotional response to odors; the thalamic-orbitofrontal pathway is thought to mediate the conscious perception of odors.

Gustatory System

LO 7.18 Describe the gustatory system.

Taste receptor cells are found on the tongue and also throughout the gastrointestinal tract (see Nolden & Feeney, 2020). On the tongue, they typically occur in clusters of 50 to 100 called **taste buds** (see Barretto et al., 2015) that are often located around small protuberances called *papillae* (singular *papilla*). The relation between taste receptors, taste buds, and papillae is illustrated in Figure 7.19.

The 50 to 100 receptor cells that compose each taste bud is said to be one of three types: (1) cells that detect bitter, sweet and *umami* (savory); (2) cells that detect sour; and (3) cells that detect salty (see Roper & Chaudhari, 2017). In each taste bud, only one of the receptor cells, the *presynaptic cell*, synapses onto the neuron carrying signals away from the bud; communication among the other cells of a taste bud appears to occur via gap junctions (see Dando & Roper, 2009). Like olfactory receptor cells, gustatory receptor cells survive only a few weeks before being replaced by new cells. The tastes that have been most studied are sweet, sour, bitter, salty, and *umami*, but a case can be made for others (see Liman, Zhang, & Montell, 2014; Vincis & Fontanini, 2016).

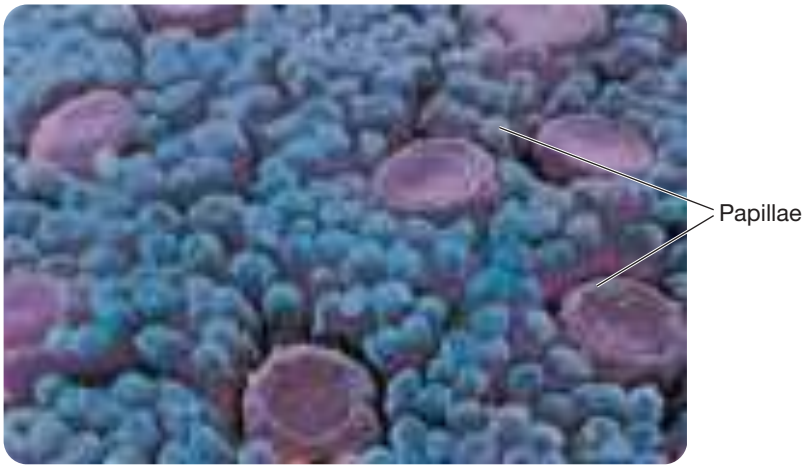
Taste transduction for sweet, umami, and bitter is mediated by *metabotropic* receptors. There are two metabotropic receptors for sweet, one for umami, and about 25 for bitter. By contrast, taste transduction for salty and sour is mediated by *ionotropic* receptors. Sour is transduced by three different ionotropic receptors, and salty is mediated by two (see Nolden & Feeney, 2020). As in the olfactory system, there appears to be only one type of receptor protein per each receptor cell.

The major pathways over which gustatory signals are conducted to the cortex are illustrated in Figure 7.20. Gustatory afferents leave the mouth as part of the *facial* (VII), *glossopharyngeal* (IX), and *vagus* (X) *cranial nerves*, which carry information from the front of the tongue, the back of the tongue, and the back of the oral cavity, respectively. These fibers all terminate in the **solitary nucleus** of the medulla, where they synapse on neurons that project to the *ventral posterior nucleus* of the thalamus. The gustatory axons of the ventral posterior nucleus project to the *primary gustatory cortex*, which is in the *insula*, an area of cortex hidden in the lateral fissure (see Linster & Fontanini, 2014). A different area of primary gustatory cortex represents each taste (see Peng et al., 2015). Secondary gustatory cortex is in the orbitofrontal cortex (see Figure 7.20). Unlike the projections of other sensory systems, the projections of the gustatory system are primarily ipsilateral.

Some evidence suggests that the primary gustatory cortex, like primary olfactory cortex, is chemotopically organized. Schoenfeld et al. (2004) measured fMRI responses to the five primary tastes and found that each primary taste produced

Figure 7.19 Taste receptors, taste buds, and papillae on the surface of the tongue, and a cross-section of a papilla that shows a taste bud and its taste receptors. Two sizes of papillae are visible in the photograph; only the larger papillae contain taste buds and receptors.

Surface of Tongue



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Cross Section of a Papilla

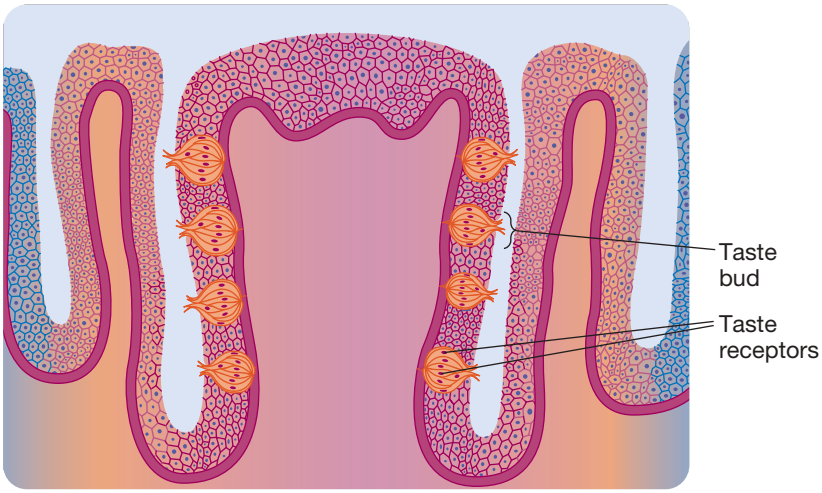
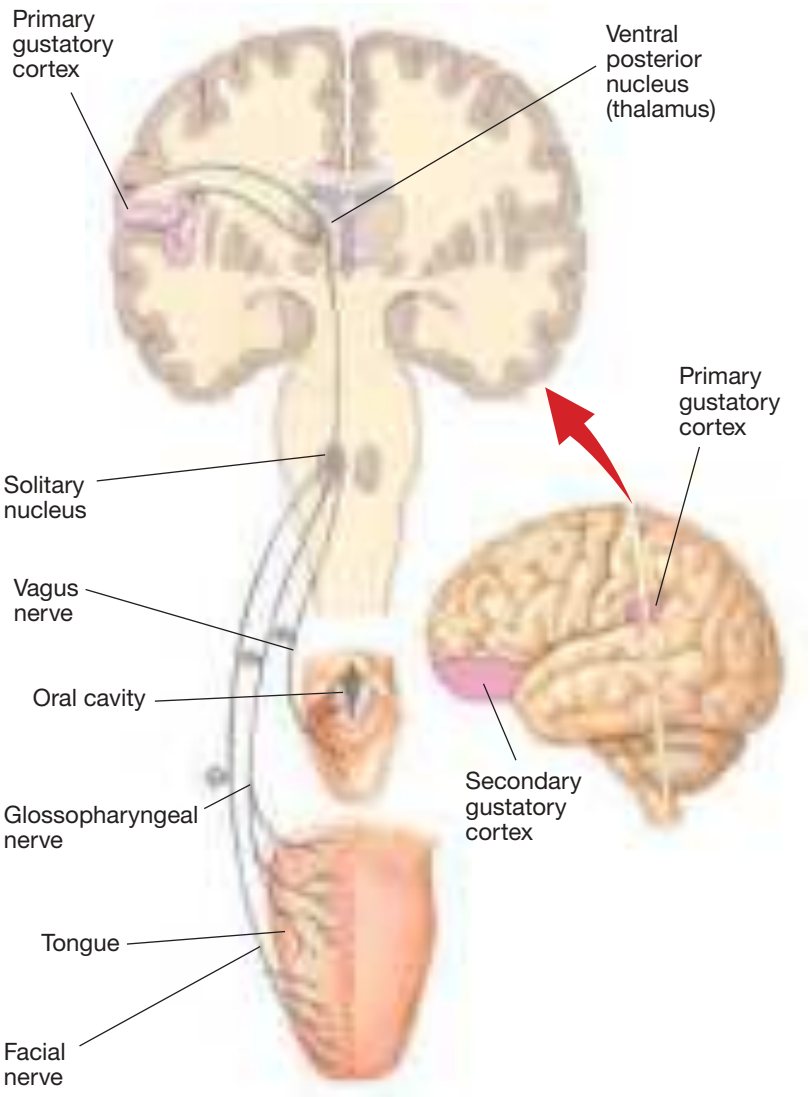


Figure 7.20 The human gustatory system.



activity in a different area of primary gustatory cortex. The chemotopic map was different in each volunteer, and there was considerable overlap of the five areas, but the map in each volunteer was stable over time. A similar finding has been reported in mice (Chen et al., 2011).

Brain Damage and the Chemical Senses

LO 7.19 **Explain the potential effects of brain damage on the chemical senses.**

The inability to smell is called **anosmia**; the inability to taste is called **ageusia**. The most common neurological cause of anosmia is a blow to the head that causes a displacement of the brain within the skull and shears the olfactory nerves where they pass through the cribriform plate. Less complete deficits in olfaction have been linked to a wide variety of neurological disorders including Alzheimer's disease, Down syndrome, epilepsy, multiple sclerosis, Korsakoff's syndrome, and Parkinson's disease (see Godoy et al., 2015).

Ageusia is rare, presumably because sensory signals from the mouth are carried via three separate pathways. However, partial ageusia, limited to the anterior two-thirds of the tongue on one side, is sometimes observed after damage to the ear on the same side of the body. This is because the branch of the facial nerve (VII) that carries gustatory information

Scan Your Brain

Now that you have reached the threshold of this chapter's final module, a module that focuses on attention, you should scan your brain to test your knowledge of the sensory systems covered in the preceding modules. Complete each sentence with terms related to the appropriate system. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your incorrect answers and omissions.

1. Information from the receptors in the muscles, joints, and balance organs about the position of the body is monitored by the _____ system.
2. The largest and deepest receptors of the skin that respond to sudden displacements of the skin but not to constant pressure are called _____.
3. Some skin receptors such as the Ruffini endings and _____ adapt slowly, allowing the static properties of tactile stimuli to become unnoticeable.
4. Most of the output of the secondary somatosensory cortex goes to the association cortex of the _____ lobe and participates in the perception of objects' shapes.
5. A rare neuropsychological condition known as _____ affects the ability to recognize one's own body parts.
6. Some of the areas of the brain implicated in pain perception are the thalamus, SI and SII, the anterior cingulate gyrus, and the _____.
7. Sexual and aggressive behavior in animals, such as hamsters, are controlled by _____.
8. Clusters of neurons that lie near the surface of the olfactory bulb are called olfactory _____.
9. The emotional response to odors is thought to be mediated by the _____ system.
10. Gustatory signals leave the back of the tongue reaching the solitary nucleus of the medulla and from there to the thalamus. The final destination is the primary gustatory cortex located in the _____.

Scan Your Brain answers: (1) proprioceptive, (2) Pacinian corpuscles, (3) Merkel's disks, (4) posterior parietal, (5) asomatognosia, (6) insula, (7) pheromones, (8) glomeruli, (9) limbic, (10) insula.

from the anterior two-thirds of the tongue passes through the middle ear.

Perception

The three previous modules examined four of our five sensory systems. However, knowing how sensory systems work leaves unanswered how we construct a rich multisensory **percept** (the outcome of perception) of the world from moment to moment. As you will see, our nervous system makes decisions about how we perceive incoming sensory information based on our prior experiences.

Role of Prior Experience in Perception

LO 7.20 Use examples to illustrate the role of experience in perception.

Prior knowledge has a major influence on how we perceive the world. For example, in our visual world, shadows usually appear beneath objects rather than above them, because the sun is our primary source of light. Moreover, our knowledge of the identity of objects affects our perception. Check It Out: How Knowledge Affects Perception on the next page illustrates each of these points (see also de Lange, Heilbron, & Kok, 2018).

Our prior knowledge about the temporal order of sensory events also affects our perception (see Nobre & van Ede, 2018). For example, through learning we come to know the order in which colored lights appear at a stoplight (e.g., green to yellow to red to green, etc.).

Perceptual Decision Making

LO 7.21 Explain perceptual decision making, using some examples of phantom percepts to illustrate.

Many researchers believe that we create mental models of the world based on predictable and recurring sensory events. According to this theory, we are "prediction machines" that actively construct models of ourselves and our world via our five senses (see de Lange, Heilbron, & Kok, 2018; Freedman & Assad, 2016; Whitney & Leib, 2018; Murray et al., 2016). That is, from moment to moment, our brain is making decisions about what we should perceive, and those decisions are based on prior experiences and current incoming sensory information. It appears that such ongoing **perceptual decision making** consumes a large proportion of the energy used by our brains (see Richmond & Zacks, 2017). The phenomenon of **bistable figures** (see Check It Out: Bistable Figures) illustrates perceptual decision making at work.

Check It Out

Bistable Figures

The image below is an example of a bistable figure: While viewing a bistable figure, our percept alternates between that of two faces and that of a chalice. Interestingly, this alternation between percepts occurs at a regular frequency, and that frequency is different from person to person (see Brascamp et al., 2018).

Even in the absence of sensory input, we still perceive. This is illustrated by the existence of **phantom percepts**: the products of perception when there is an absence of sensory input (see Mohan & Vanneste, 2017). One example of this is the phenomenon of **phantom limbs**, wherein amputees perceive the presence of their missing limb long after it has been lost to injury or amputation.

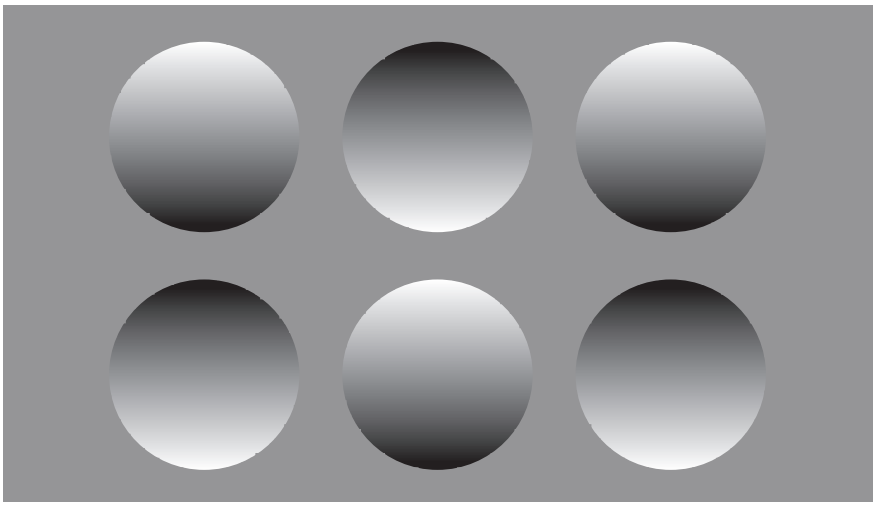
Another example is what happens when an individual is deprived of visual input later in life, such as is the case for individuals who develop *glaucoma* (a medical condition wherein there is irreversible damage to the optic nerve). Some of these individuals experience rich and complex hallucinations (e.g., people's faces, complex landscapes). This condition is known as **Charles Bonnet Syndrome** (see Mohan & Vanneste, 2017; Sacks, 2012). The characteristics of the phantom percepts in Charles Bonnet syndrome seem to be dependent on the person's experience. For example, some musicians with Charles Bonnet syndrome experience phantom percepts of musical notation (see Sacks, 2013).

The mechanisms by which we make perceptual decisions are not entirely clear, but there is mounting evidence that such decisions are mediated by several areas in the brain, including

Check It Out

How Knowledge Affects Perception

The image below illustrates that we perceive the world based on our knowledge of the how the world works. That is, you perceive each circle as either convex or concave, such that in all instances it looks like the shading is due to a light source coming from above. This is presumably because we know that our most common source of light, the sun, shines down on objects.



The next part of this Check It Out requires that you be the experimenter! Cover up the right image and then ask someone else what they see in the left image. Next, uncover the right image. Now, ask them what they see in the left image. The fact that they have a richer percept (i.e., they see the dalmation in it) of the left image after viewing the right image illustrates the effect of prior knowledge on perception.

Mala Iryna/Shutterstock

the dorsolateral prefrontal cortex and the posterior parietal cortex (see Brascamp et al., 2018; Fleming, van der Putten, & Daw, 2018). Interestingly, both structures are involved in the decision to initiate a physical movement (see Chapter 8). That is, those brain structures involved in action decision making are the same as those implicated in perceptual decision making.

The Binding Problem

LO 7.22 Explain the binding problem and describe two potential solutions to it.

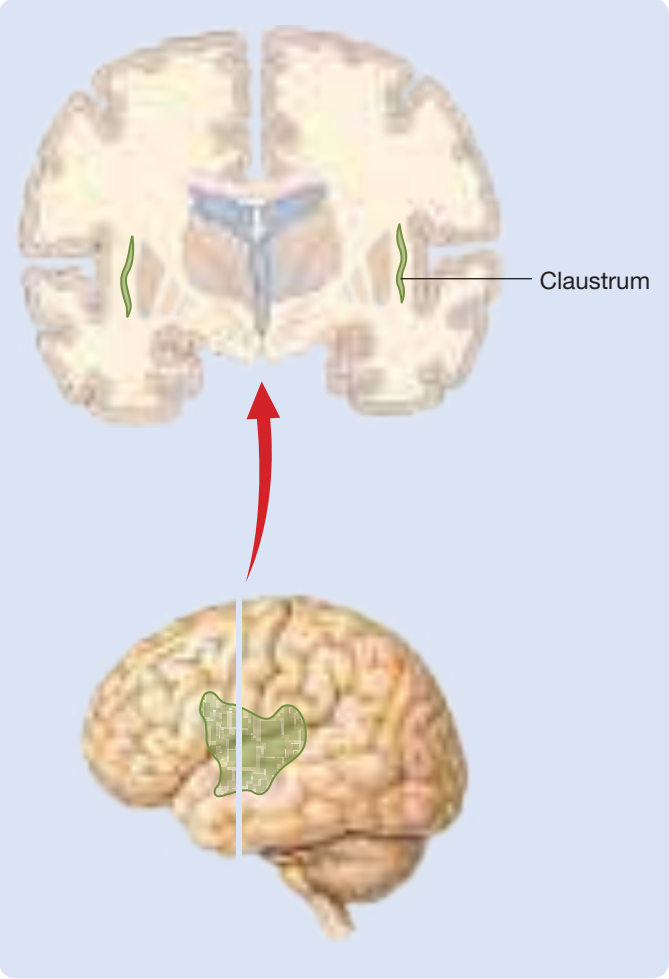
Sensory systems are characterized by a division of labor: Multiple specialized areas, at multiple levels, are interconnected by multiple parallel pathways. For example, each

area of the visual system is specialized for perceiving specific aspects of visual scenes (e.g., shape, color, movement). Yet, complex stimuli are normally perceived as integrated wholes, not as combinations of independent attributes. How does the brain combine individual sensory attributes to produce integrated perceptions? This is called **the binding problem** (see Bizley, Maddox, & Lee, 2016; Feldman, 2013; but see Di Lollo, 2012).

One possible solution to the binding problem is that there is a single area of the cortex at the top of the sensory hierarchy that receives signals from all other areas of the various sensory systems and puts them together to form a percept. One area of the brain that has received recent attention as the potential location for the binding of sensory information is the *claustrum* (see Figure 7.21), a structure that is made up of a fine sheet of neurons located just underneath the cortex towards the middle of the brain (see Goll, Atlan, & Citri, 2015; Tan et al., 2017).

An alternative solution to the binding problem is that there is no single area responsible for putting together perceptions. Rather, perceptions might be the result of multiple interactions at each of the cortical levels of the hierarchy.

Figure 7.21 The location of the claustrum.



This solution is informed by the study of communication between sensory areas in the cortex. For example, we now know that, beginning at the level of the primary sensory cortices, there is integration of information from multiple senses (see Murray et al., 2016). Accordingly, it might be the case that binding emerges from the constant exchange of information between the many sensory cortices, both within and across sensory modalities (see Bizley, Maddox, & Lee, 2016). A role for subcortical structures in this information exchange has also been suggested (see Romo & Rossi-Pool, 2020).

Selective Attention

We consciously perceive only a small subset of the many stimuli that excite our sensory organs at any one time and largely ignore the rest (see Peelen & Kastner, 2014; Squire et al., 2013). The process by which this occurs is selective attention.

Characteristics of Selective Attention

LO 7.23 Describe the two characteristics of selective attention and explain what is meant by exogenous versus endogenous attention.

Selective attention has two characteristics: It improves the perception of the stimuli that are its focus, and it interferes with the perception of the stimuli that are not its focus (see Sprague, Saproo, & Serences, 2015). For example, if you focus your attention on a potentially important announcement in a noisy airport, your chances of understanding it increase, but your chances of understanding a simultaneous comment from a traveling companion decrease.

Attention can be focused in two different ways: by internal cognitive processes (*endogenous attention*) or by external events (*exogenous attention*)—see Chica, Bartolomeo, and Lupiáñez (2013), but see Macaluso and Doricchi (2013). For example, your attention can be focused on a tabletop because you are searching for your keys (endogenous attention), or it can be drawn there because your cat tipped over a lamp (exogenous attention). Endogenous attention is thought to be mediated by **top-down** (from higher to lower levels) neural mechanisms, whereas exogenous attention is thought to be mediated by **bottom-up** (from lower to higher levels) neural mechanisms (see Miller & Buschman, 2013).

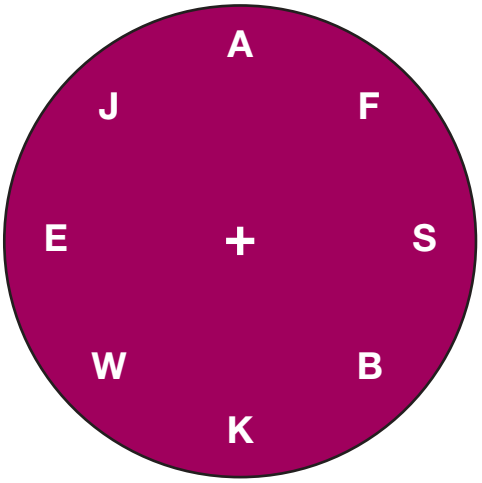
Eye movements often play an important role in visual attention, but it is important to realize that visual attention can be shifted without shifting the direction of visual focus (see Krauzlis, Lovejoy, & Zénon, 2013). To prove this to yourself, look at the next Check It Out demonstration.

One other important characteristic of selective attention has been called the cocktail-party phenomenon (see Du et al., 2011). The **cocktail-party phenomenon** is the fact that even when you are focusing so intently on one conversation

Check It Out

Shifting Visual Attention Without Shifting Visual Focus

Fix your gaze on the +; concentrate on it. Next, shift your attention to one of the letters without shifting your gaze from +. Now, shift your attention to other letters, again without shifting your gaze from the +. You have experienced *covert attention*—a shift of visual attention without any corresponding eye movement. A change in visual attention that involves a shift in gaze is called *overt attention*.



that you are totally unaware of the content of other conversations going on around you, the mention of your name in one of the other conversations will immediately gain access to your consciousness. This phenomenon suggests that your brain can block from conscious awareness all stimuli except those of a particular kind while still unconsciously monitoring the blocked-out stimuli just in case something comes up that requires your attention.

Change Blindness

LO 7.24 Describe the phenomenon of change blindness.

There is no better illustration of the importance of attention than the phenomenon of change blindness (Land, 2014). To study **change blindness**, a volunteer is shown a photo on a computer screen and asked to report any change in the image as soon as it is noticed. In fact, the image is composed of two images that alternate with a delay of less than 0.1 second between them. The two photographic images are identical except for one gross feature. For example, the two images in Figure 7.22 are identical except that the picture in the center of the wall is missing from one. You might think that any person would immediately notice the picture disappearing and reappearing. But this is not what happens. Most volunteers spend many seconds staring at the image—searching, as instructed, for some change—before they notice the disappearing and reappearing picture. When they finally notice it, they wonder in amazement why it took them so long.

Why does change blindness occur? It occurs because, contrary to our impression, when we view a scene, we have absolutely no memory for parts of the scene that are not the focus of our attention. When viewing the scene in Figure 7.22, most volunteers attend to the two people and do not notice when the picture disappears from the wall between them. Because they have no memory of the parts of the image to which they did not attend, they are not aware when those parts change.

The change blindness phenomenon does not occur without the brief (i.e., less than 0.1 second) intervals between

Figure 7.22 The change blindness phenomenon. These two illustrations were continually alternated, with a brief (less than 0.1 second) interval between each presentation, and the subjects were asked to report any changes they noticed. Amazingly, it took most of them many seconds to notice the disappearing and reappearing building in the distance, behind the person on the left.

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images. Without the intervals, no memory is required and the changes are perceived immediately.

Neural Mechanisms of Attention

LO 7.25 Describe the neural mechanisms of attention.

Where do top-down attentional influences on sensory systems originate? There is a general consensus that both prefrontal cortex and posterior parietal cortex play major roles in directing top-down attention (see Baluch & Itti, 2011; Noudoost et al., 2010).

Moran and Desimone (1985) were the first to demonstrate the effects of attention on neural activity. They trained monkeys to stare at a fixation point on a screen while they recorded the activity of neurons in a prestriate area that was part of the ventral stream and particularly sensitive to color. In one experiment, they recorded from individual neurons that responded to either red or green bars of light in their receptive fields. When the monkey was trained to perform a task that required attention to the red cue, firing of the neurons in response to the red cue was increased, while the response to the green cue was reduced. The opposite happened when the monkey was required to attend to green.

Experiments paralleling those in monkeys have been conducted in humans using functional brain-imaging techniques. For example, Corbetta and colleagues (1990) presented a collection of moving, colored stimuli of various shapes and asked volunteers to discriminate among the stimuli based on their movement, color, or shape. Attention to shape or color produced increased activity in areas of the ventral stream; attention to movement produced increased activity in an area of the dorsal stream.

In another study of attention in human volunteers, Ungerleider and Haxby (1994) showed volunteers a series of faces. The volunteers were asked whether the faces belonged to the same person or whether they were located in the same position relative to the frame. When they were attending to identity, regions of the ventral stream were more active; when they were attending to position, regions of the dorsal stream were more active.

The preceding studies indicate the principle by which the neural mechanisms of selective attention work. Selective attention works by strengthening the neural responses to attended-to stimuli and by weakening the responses to others (see Buschman, 2015; Luo & Maunsell, 2015). This dual mechanism has been termed a *push–pull mechanism* (see Stevens & Bavelier, 2012).

Some neural mechanisms of attention involve a surprising degree of neural plasticity. For example, the location of the receptive fields of visual neurons, which had been assumed to be a static property of visual neurons, can be shifted by spatial attention (see Anton-Erxleben & Carrasco, 2013). Recording from neurons in an area of monkey secondary visual cortex in the dorsal stream, Wommelsdorf and colleagues (2006) found that the receptive fields of many of the neurons shifted toward points in the visual field to which the subjects were attending. Similarly, Rolls (2008) found that visual receptive fields of inferotemporal cortex neurons shrink to become little more than the size of objects on which they are focusing.

Covert attention is the process of attending to a sensory stimulus without fixing one's gaze (see the Check It Out on page 209). Covert attention is of great interest to biopsychologists because it allows them to study the neural mechanisms of shifts in **attentional gaze** (i.e., the shift in attention from one perceptual object to another) without worrying about the confounding effects of eye movements. Studies of the neural mechanisms of attentional gaze shifts have identified the **frontal eye field** (an area on the ventral surface of the frontal cortex) as important.

The frontal eye field, which is also active during eye movements, is active during shifts in attentional gaze. Moreover, stimulation of neurons in the frontal eye field, at intensities below the threshold necessary to elicit eye movements, leads to improvements in the detection of stimuli via covert attention (see Moore & Zirnsak, 2017). Thus, it appears that the frontal eye field mediates shifts in visual attention, though other brain areas have also been implicated (e.g., Schmitz & Duncan, 2018).

If you concluded from the foregoing discussion that most of the research on the neural mechanisms of selective attention has focused on visual attention, you would be correct. However, there are also some studies of attention to auditory (e.g., Shamma, Elhilali, & Micheyl, 2011), somatosensory (e.g., Fujiwara et al., 2002), gustatory (e.g., Stevenson, 2012; Veldhuizen, Gitelman, & Small, 2012), and olfactory (e.g., Veldhuizen & Small, 2011) stimuli.

Simultanagnosia

LO 7.26 Describe the disorder of attention known as simultanagnosia.

We have not forgotten that we asked you to think about the patient whose case opened this chapter. He could identify objects in any part of his visual field if they were presented individually; thus, he was not suffering from blindness or other visual field-defects. His was a disorder of attention called **simultanagnosia**. Specifically, he suffered from *visual-simultanagnosia*—a difficulty in attending visually to more than one object at a time. Because the dorsal stream (which includes the posterior parietal association cortex) is responsible for visually localizing objects in space, you may have hypothesized that the patient's problem was associated with damage to this area. If you did, you were correct. Simultanagnosia is usually associated with bilateral damage to the posterior parietal cortex.

Themes Revisited

The clinical implications theme was prominent in this chapter, but you saw it in a different light. Previous chapters discussed how biopsychological research is leading to the development of new treatments; this chapter focused exclusively on what particular clinical cases have revealed about the organization of healthy sensory systems. The following cases played a key role in this chapter: the patient with visual simultanagnosia; Dr. P., the visual agnosic who mistook his wife for a hat; Aunt Betty, the asomatognosic who lost the left side of her body; Miss C., the student who felt no pain and died as a result; and W.M., the man who reduced his scotoma with his hand.

The neuroplasticity theme was also developed in this chapter: the neuroplasticity theme and the evolutionary perspective theme. Although this chapter did not systematically discuss the plasticity of sensory systems, three important examples of sensory system plasticity were mentioned: the effects of tinnitus on the auditory system, partial recovery of vision in a scotoma by placing a hand in the scotoma, and the movement of the receptive fields of visual neurons toward a location that is the focus of attention.

The thinking creatively theme came up once. The case of Miss C. taught us that pain is a positive sensation that we can't live without.

The two emerging themes were also present in this chapter. The thinking about epigenetics theme arose when we saw that epigenetic mechanisms are important for neuropathic pain and that drug therapies are being developed to alter those epigenetic mechanisms. The consciousness theme was present throughout this chapter, though it was truly brought to the forefront in the modules on perception and attention.

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Sensation, p. 185
Perception, p. 185

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Secondary sensory cortex, p. 185
Association cortex, p. 185
Hierarchical organization, p. 185
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Chapter 8
The Sensorimotor System

How You Move

Matteo Carta/Alamy Stock Photo

Chapter Overview and Learning Objectives

Three Principles of Sensorimotor Function	**LO 8.1**	In the context of the sensorimotor system, explain what *hierarchically organized* means.
	LO 8.2	Explain the important role of sensory input for motor output.
	LO 8.3	Describe how learning changes the nature and locus of sensorimotor control.
	LO 8.4	Describe and/or draw the general model of sensorimotor function.
Sensorimotor Association Cortex	**LO 8.5**	Explain the role of the posterior parietal cortex in sensorimotor function and describe what happens when it is damaged or stimulated.
	LO 8.6	Explain the role of the dorsolateral prefrontal association cortex in sensorimotor function and describe the response properties of neurons in this region of cortex.

Secondary Motor Cortex	**LO 8.7** Explain the general role of areas of secondary motor cortex.
	LO 8.8 Describe the major features of mirror neurons and explain why they have received so much attention from neuroscientists.
Primary Motor Cortex	**LO 8.9** Describe the conventional view of primary motor cortex function and the evidence upon which it was based.
	LO 8.10 Describe the current view of primary motor cortex function and the evidence upon which it is based.
Cerebellum and Basal Ganglia	**LO 8.11** Describe the structure and connectivity of the cerebellum and explain the current view of cerebellar function.
	LO 8.12 Describe the anatomy of the basal ganglia and explain the current view of their function.
Descending Motor Pathways	**LO 8.13** Compare and contrast the two dorsolateral motor pathways and the two ventromedial motor pathways.
Sensorimotor Spinal Circuits	**LO 8.14** Describe the components of a motor unit and distinguish between the different types of muscles.
	LO 8.15 Describe the receptor organs of tendons and muscles.
	LO 8.16 Describe the stretch reflex and explain its mechanism.
	LO 8.17 Describe the withdrawal reflex and explain its mechanism.
	LO 8.18 Explain what is meant by *reciprocal innervation*.
	LO 8.19 Explain recurrent collateral inhibition.
	LO 8.20 Describe the phenomenon of walking and the degree to which it is controlled by spinal circuits.
Central Sensorimotor Programs and Learning	**LO 8.21** Explain what is meant by a hierarchy of central sensorimotor programs and explain the importance of this arrangement for sensorimotor functioning.
	LO 8.22 Describe the various characteristics of central sensorimotor programs.
	LO 8.23 Explain how the classic Jenkins and colleagues PET study of simple motor learning summarizes the main points of this chapter.
	LO 8.24 Describe two examples of neuroplasticity—one at the cortical level and one at the subcortical level.

The evening before we started to write this chapter, I (JP) was standing in a checkout line at the local market. As I waited, I scanned the headlines on the prominently displayed magazines—WOMAN GIVES BIRTH TO CAT; FLYING SAUCER LANDS IN CLEVELAND SHOPPING MALL; HOW TO LOSE 20 POUNDS IN 2 DAYS. Then, my mind began to wander, and I started to think about beginning to write this chapter. That is when I began to watch Rhonelle's movements, and to wonder about the neural system that controlled them. Rhonelle is a cashier—the best in the place.

The Case of Rhonelle, the Dexterous Cashier

I was struck by the complexity of even Rhonelle's simplest movements. As she deftly transferred a bag of tomatoes to the scale, there was a coordinated adjustment in almost every part of her body. In addition to her obvious finger, hand, arm, and shoulder movements, coordinated movements of her head and eyes tracked her hand to the tomatoes; and there were adjustments in the muscles of her feet, legs, trunk, and other arm, which kept her from lurching forward. The accuracy of these responses suggested that they were guided in part by the patterns of visual, somatosensory, and vestibular changes they produced. (The term *sensorimotor* in the title of this chapter formally recognizes the critical contribution of sensory input to guiding motor output.)

As my purchases flowed through her left hand, Rhonelle scanned the items with her right hand and bantered with Rich, the bagger. I was intrigued by how little of what Rhonelle was doing appeared to be under her conscious control. She made general decisions about which items to pick up and where to put them, but she seemed to give no thought to the exact means by which these decisions were carried out. Each of her responses could have been made with an infinite number of different combinations of finger, wrist, elbow, shoulder, and body adjustments; but somehow she unconsciously picked one. The higher parts of her sensorimotor system—perhaps her cortex—seemed to issue conscious general commands to other parts of the system, which unconsciously produced a specific pattern of muscular responses that carried them out.

The automaticity of Rhonelle's performance was a far cry from the slow, effortful responses that had characterized her first days at the market. Somehow, experience had integrated her individual movements into smooth sequences, and it seemed to have transferred the movements' control from a mode that involved conscious effort to one that did not.

I was suddenly jarred from my contemplations by a voice. "Sir, excuse me, sir, that will be $78.65," Rhonelle said, with just a hint of delight at catching me mid-daydream. I hastily paid my bill, muttered "thank you," and scurried out of the market.

As we write this, I am smiling both at my own embarrassment and at the thought that Rhonelle has unknowingly introduced you to three principles of sensorimotor control that are the foundations of this chapter: (1) The sensorimotor system is hierarchically organized. (2) Motor output is guided by sensory input. (3) Learning can change the nature and the locus of sensorimotor control.

Three Principles of Sensorimotor Function

Before getting into the details of the sensorimotor system, let's take a closer look at the three principles of sensorimotor function introduced by Rhonelle. You will better appreciate these principles if you recognize that they also govern the operation of any large, efficient company—perhaps because that is another system for controlling output that has evolved in a competitive environment. You may find this metaphor useful in helping you understand the principles of sensorimotor system organization—many scientists find that metaphors help them think creatively about their subject matter.

The Sensorimotor System Is Hierarchically Organized

LO 8.1 **In the context of the sensorimotor system, explain what *hierarchically organized* means.**

The operation of both the sensorimotor system and a large, efficient company is directed by commands that cascade down through the levels of a hierarchy (see Sadnicka et al., 2017)—from the association cortex or the company president (the highest levels) to the muscles or the workers (the lowest levels). Like the orders issued from the office of a company president, the commands that emerge from the association cortex specify general goals rather than specific plans of action. Neither the association cortex nor the company president routinely gets involved in the details. The main advantage of this *hierarchical organization* is that the higher levels of the hierarchy are left free to perform more complex functions.

Both the sensorimotor system and a large, efficient company are parallel hierarchical systems; that is, they are hierarchical systems in which signals flow between levels over multiple paths. This parallel structure enables the association cortex or company president to exert control over the lower levels of the hierarchy in more than one way. For example, the association cortex can directly inhibit an eye blink reflex to allow the insertion of a contact lens, just as a company president can personally organize a delivery to an important customer (see McDougle, Ivry, & Taylor, 2016).

The sensorimotor and company hierarchies are also characterized by *functional segregation*. That is, each level of the sensorimotor and company hierarchies tends to be composed of different units (neural structures or departments), each of which performs a different function.

Journal Prompt 8.1

Can you think of another effective metaphor for the sensorimotor system?

In summary, the sensorimotor system—like the sensory systems you read about in Chapter 7—is a parallel, functionally segregated, hierarchical system. The main difference between the sensory systems and the sensorimotor system is the primary direction of information flow. In sensory systems, information mainly flows up through the hierarchy; in the sensorimotor system, information mainly flows down.

Motor Output Is Guided by Sensory Input

LO 8.2 Explain the important role of sensory input for motor output.

Efficient companies are flexible. They continuously monitor the effects of their own activities, and they use this information to fine-tune their activities. The sensorimotor system does the same (see Azim, Fink, & Jessell, 2014; Danna & Velay, 2015; Scott, 2016). The eyes, the organs of balance, and the receptors in skin, muscles, and joints all monitor the body's responses, and they feed their information back into sensorimotor circuits. In most instances, this **sensory feedback** plays an important role in directing the continuation of the responses that produced it. The only responses that are not normally influenced by sensory feedback are *ballistic movements*—brief, all-or-none, high-speed movements, such as swatting a fly.

Behavior in the absence of just one kind of sensory feedback—the feedback carried by the somatosensory nerves of the arms—was studied in G.O., a former darts champion (Rothwell et al., 1982).

The Case of G.O., the Man with Too Little Feedback

An infection had selectively destroyed the somatosensory nerves of G.O.'s arms. He had great difficulty performing intricate responses such as doing up his buttons or picking up coins, even under visual guidance. Other difficulties resulted from his inability to adjust his motor output in light of unanticipated external disturbances; for example, he could not keep from spilling a cup of coffee if somebody brushed against him. However, G.O.'s greatest problem was his inability to maintain a constant level of muscle contraction.

The result of his infection was that even simple tasks requiring a constant motor output to the hand required continual visual monitoring. For example, when carrying a suitcase, he had to watch it to reassure himself that he had not dropped it. However, even visual feedback was of little use to him in tasks requiring a constant force, tasks such as grasping a pen while writing or holding a cup. In these cases, he had no indication of the pressure that he was exerting on the object; all he saw was the pen or cup slipping from his grasp.

Many adjustments in motor output that occur in response to sensory feedback are controlled unconsciously by the lower levels of the sensorimotor hierarchy without the involvement of the higher levels (see Deliagina, Zelenin, & Orlovsky, 2012). In the same way, large companies run more efficiently if the interns do not check with the company president each time they encounter a minor problem.

Learning Changes the Nature and Locus of Sensorimotor Control

LO 8.3 Describe how learning changes the nature and locus of sensorimotor control.

When a company is just starting up, each individual decision is made by the company president after careful consideration. However, as the company develops, many individual actions are coordinated into sequences of prescribed procedures routinely carried out by personnel at lower levels of the hierarchy.

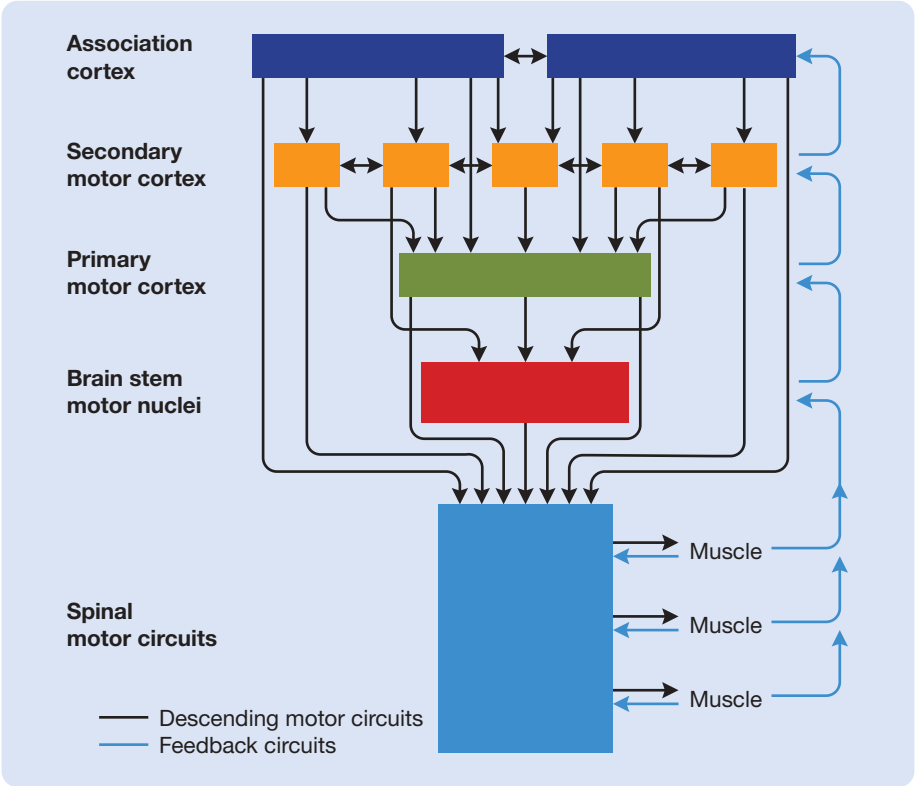
Similar changes occur during sensorimotor learning (see Bassett et al., 2015). During the initial stages of motor learning, each individual response is performed under conscious control; then, after much practice, individual responses become organized into continuous integrated sequences of action that flow smoothly and are adjusted by sensory feedback without conscious regulation. If you think for a moment about the sensorimotor skills you have acquired (e.g., typing, swimming, knitting, basketball playing, dancing, piano playing), you will appreciate that the organization of individual responses into continuous motor programs and the transfer of their control to lower levels of the CNS characterize most sensorimotor learning.

General Model of Sensorimotor System Function

LO 8.4 Describe and/or draw the general model of sensorimotor function.

Figure 8.1 is a model that illustrates several principles of sensorimotor system organization; it is the framework of this chapter. Notice its hierarchical structure, the functional

Figure 8.1 A general model of the sensorimotor system. Notice its hierarchical structure, functional segregation, parallel descending pathways, and feedback circuits.



segregation of the levels (e.g., of secondary motor cortex), the parallel connections between levels, and the numerous feedback pathways.

This chapter focuses on the neural structures that play important roles in the control of voluntary behavior (e.g., picking up an apple). It begins at the level of association cortex and traces major motor signals as they descend the sensorimotor hierarchy to the skeletal muscles that ultimately perform the movements.

Sensorimotor Association Cortex

Association cortex is at the top of your sensorimotor hierarchy. There are two major areas of sensorimotor association cortex: the posterior parietal association cortex and the dorsolateral prefrontal association cortex. Posterior parietal cortex and the dorsolateral prefrontal cortex are each composed of several different areas, each with different functions (see Davare et al., 2011; Wilson et al., 2010). However, there is no general consensus on how best to divide either of them for analysis or even how comparable the areas are in humans, monkeys, and rats (see Teixeira et al., 2014; Turella & Lingnau, 2014).

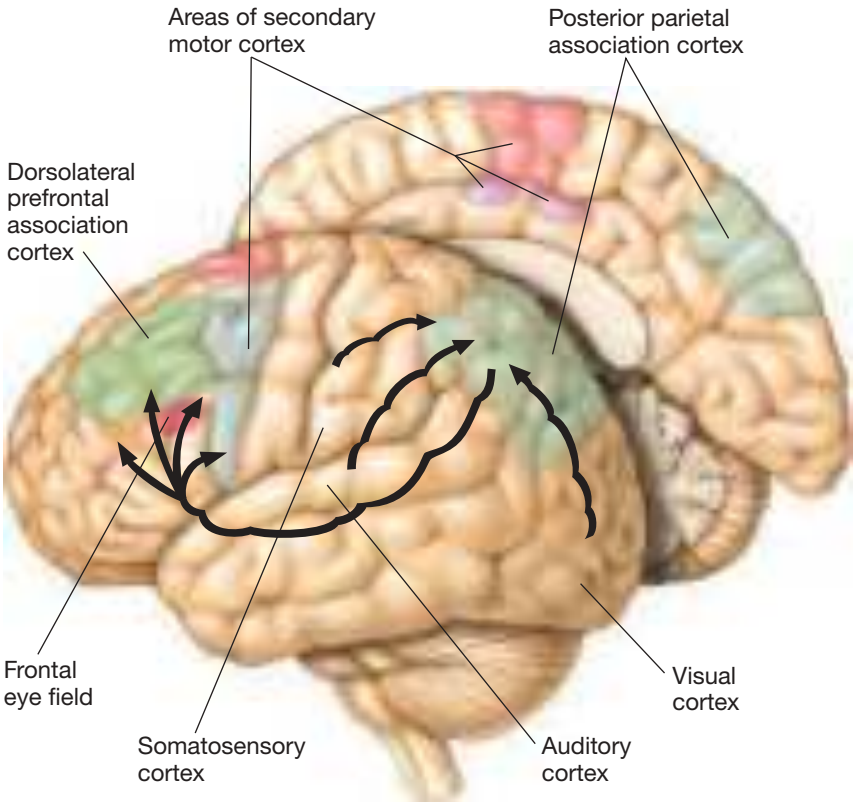
Posterior Parietal Association Cortex

LO 8.5 Explain the role of the posterior parietal cortex in sensorimotor function and describe what happens when it is damaged or stimulated.

Before an effective movement can be initiated, certain information is required. The nervous system must know the original positions of the parts of the body that are to be moved, and it must know the positions of any external objects with which the body is going to interact. The **posterior parietal association cortex** (the portion of parietal neocortex posterior to the primary somatosensory cortex) plays an important role in integrating these two kinds of information, in directing behavior by providing spatial information, and in directing attention (Freedman & Ibos, 2018; Hutchinson et al., 2014; Kuang, Morel, & Gail, 2015; Wilber et al., 2014).

You learned in Chapter 7 that the posterior parietal cortex is classified as *association cortex* because it receives input from more than one sensory system. It receives information from the three sensory systems that play roles in the localization of the body and external objects in space: the visual system, the auditory system, and the somatosensory system (see Figure 8.2)—see Sereno and Huang (2014). In turn, much of the output of the posterior parietal cortex goes to areas of motor cortex, which are located in the frontal

Figure 8.2 The major cortical input and output pathways of the posterior parietal association cortex. Shown are the lateral surface of the left hemisphere and the medial surface of the right hemisphere.



cortex: to the *dorsolateral prefrontal association cortex*, to the various areas of *secondary motor cortex*, and to the **frontal eye field**—a small area of prefrontal cortex that controls both eye movements and shifts in attention (see Moore & Zirnsak, 2015; Figure 8.2). Electrophysiological studies in macaque monkeys and functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) studies in humans indicate that the posterior parietal cortex contains a mosaic of small areas, each specialized for guiding particular movements of eyes, head, arms, or hands (Man et al., 2015; Wang et al., 2015).

Desmurget and colleagues (2009) applied electrical stimulation to the inferior portions of the posterior parietal cortexes of conscious neurosurgical patients. At low current levels, the patients experienced an intention to perform a particular action, and, at higher current levels, they felt that they had actually performed it. However, in neither case did the action actually occur (see Desmurget & Sirigu, 2012).

Damage to the posterior parietal cortex can produce a variety of deficits, including deficits in the perception and memory of spatial relationships, in accurate reaching and grasping, in the control of eye movement, and in attention (see Andersen et al., 2014; Turella & Lingnau, 2014). However, apraxia and contralateral neglect are the two most striking consequences of posterior parietal cortex damage.

Apraxia is a disorder of voluntary movement that is not attributable to a simple motor deficit (e.g., not to paralysis or weakness) or to any deficit in comprehension or motivation (see Niessen, Fink, & Weiss, 2014). Remarkably, patients with apraxia have difficulty making specific movements when they are requested to do so, particularly when the movements are out of context; however, they can often readily perform the very same movements under natural conditions when they are not thinking about what they are doing. For example, a carpenter with apraxia who has no difficulty at all hammering a nail during the course of her work might not be able to demonstrate hammering movements when requested to make them, particularly in the absence of a hammer. Although its symptoms are bilateral, apraxia is often caused by unilateral damage to the left posterior parietal cortex or its connections (Hoeren et al., 2014; Niessen, Fink, & Weiss, 2014).

Contralateral neglect, the other striking consequence of posterior parietal cortex damage, is a disturbance of a patient's ability to respond to stimuli on the side of the body opposite (contralateral) to the side of a brain lesion in the absence of simple sensory or motor deficits. Most patients with contralateral neglect often behave as if the left side of their world does not exist, and they often fail to appreciate that they have a problem (see Li & Malhotra, 2015). The disturbance is often associated with large lesions of the right posterior parietal cortex, though damage to other brain regions has also been implicated (see Karnath & Otto, 2012). Mrs. S. suffered from contralateral neglect after a massive stroke to the posterior portions of her right hemisphere (Sacks, 1999).

The Case of Mrs. S., the Woman Who Turned in Circles

After her stroke, Mrs. S. could not respond to things on her left—including objects and parts of her own body. For example, she often put makeup on the right side of her face but ignored the left.

Mrs. S.'s left-side contralateral neglect created many problems for her, but a particularly bothersome one was that she had difficulty getting enough to eat. When a plate of food was put directly in front of her, she could see only the food on the right half of the plate, and she ate only that half, even if she was very hungry. However, Mrs. S. developed an effective way of getting more food. If she was still hungry after completing a meal, she turned her wheelchair to the right in a full circle until

the remaining half of her meal appeared once more directly in front of her. Then, she ate that remaining food, or more precisely, she ate the right half of it. If she was still hungry after that, she turned once again in a circle to the right until the remaining quarter of her meal appeared, and she ate half of that . . . and so on.

Most patients with contralateral neglect have difficulty responding to things to the left. But to the left of what? For most patients with contralateral neglect, the deficits in responding occur for stimuli to the left of their own bodies, referred to as *egocentric left* (see Karnath, 2015). Egocentric left is partially defined by gravitational coordinates: When patients tilt their heads, their field of neglect is not normally tilted with it.

Some patients also tend not to respond to the left sides of objects, regardless of where the objects are in their visual fields (see Karnath, 2015). These patients, who are said to suffer from *object-based contralateral neglect*, fail to respond to the left side of objects (e.g., the left hand of a statue) even when the objects are presented horizontally or upside down (see Adair & Barrett, 2008).

As you will recall, failure to perceive an object consciously does not necessarily mean the object is not perceived. Indeed, two types of evidence suggest that information about objects that are not noticed by patients with contralateral neglect may be unconsciously perceived (see Jerath & Crawford, 2014). First, when objects were repeatedly presented in the same location to the left of patients with contralateral neglect, they tended to look more in that general direction on future trials, although they were unaware of the objects (Geng & Behrmann, 2002). Second, patients could more readily identify fragmented (partial) drawings viewed to their right if complete versions of the drawings had previously been presented to the left, where they were not consciously perceived (Vuilleumier et al., 2002).

Dorsolateral Prefrontal Association Cortex

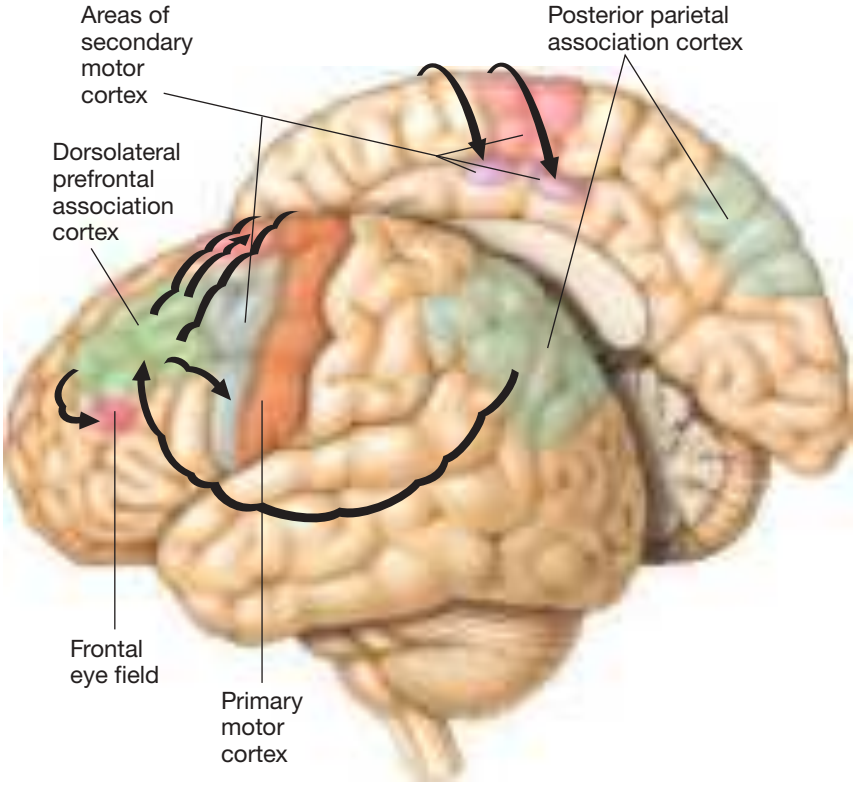
LO 8.6 **Explain the role of the dorsolateral prefrontal association cortex in sensorimotor function and describe the response properties of neurons in this region of cortex.**

The other large area of association cortex that has important sensorimotor functions is the **dorsolateral prefrontal association cortex** (see Kaller et al., 2011). It receives projections from the posterior parietal cortex, and it sends projections to areas of *secondary motor cortex*, to *primary motor cortex*, and to the *frontal eye field*. These projections are shown in Figure 8.3.

Several studies have characterized the activity of monkey dorsolateral prefrontal neurons while the monkeys identify and respond to objects (e.g., Rao, Rainer, & Miller, 1997). The activity of some neurons depends on the characteristics of objects; the activity of others depends on the locations of objects; and the activity of still others depends on a combination of both. The activity of other dorsolateral prefrontal neurons is related to the response rather than to the object. These neurons typically begin to fire before the response and continue to fire until the response is complete. Neurons in many cortical motor areas begin to fire in anticipation of a motor activity (see Rigato, Murakami, & Mainen, 2014; Siegel, Buschman, & Miller, 2015), but those in the dorsolateral prefrontal association cortex tend to fire first.

The response properties of dorsolateral prefrontal neurons suggest that decisions to initiate voluntary movements may be made in this area of cortex, but these decisions depend on critical interactions with posterior parietal cortex and other areas of frontal cortex (Lee, Seo, & Jung, 2012; Ptak, Schnider, & Fellrath, 2017).

Figure 8.3 The major cortical input and output pathways of the dorsolateral prefrontal association cortex. Shown are the lateral surface of the left hemisphere and the medial surface of the right hemisphere. Not shown are the major projections back from dorsolateral prefrontal cortex to posterior parietal cortex.



Secondary Motor Cortex

Areas of **secondary motor cortex** are those that receive much of their input from association cortex (i.e., posterior parietal cortex and dorsolateral prefrontal cortex) and send much of their output to primary motor cortex (see Figure 8.4). For many years, only two areas of secondary motor cortex were known: the supplementary motor area and the premotor cortex. Both of these large areas are clearly visible on the lateral surface of the frontal lobe, just anterior to the *primary motor cortex*. The **supplementary motor area** wraps over the top of the frontal lobe and extends down its medial surface into the longitudinal fissure, and the **premotor cortex** runs in a strip from the supplementary motor area to the lateral fissure.

Identifying the Areas of Secondary Motor Cortex

LO 8.7 **Explain the general role of areas of secondary motor cortex.**

The simple two-area conception of secondary motor cortex has become more complex. Neuroanatomical and neurophysiological research with monkeys has made a case for at least eight areas of secondary motor cortex in each hemisphere, each with its own subdivisions (Nachev, Kennard, & Husain, 2008). Although most of the research on secondary motor cortex has been done in monkeys, functional brain-imaging studies have suggested that human secondary motor cortex has a comparable organization (see Caminiti, Innocenti, & Battaglia-Mayer, 2015).

To qualify as secondary motor cortex, an area must be appropriately connected with association and secondary motor areas (see Figure 8.4). Electrical stimulation of an area of secondary motor cortex typically elicits complex movements, often involving both sides of the body. Neurons in an area of secondary motor cortex often become more active just prior to the initiation of a voluntary movement and continue to be active throughout the movement.

In general, areas of secondary motor cortex are thought to be involved in the programming of specific patterns of movements after taking general instructions from dorsolateral prefrontal cortex (see Pearce & Moran, 2012). Evidence of such a function comes from brain-imaging studies in which the patterns of activity in areas of secondary motor cortex have been measured while a volunteer is either imagining his or her own performance of a particular series of movements or planning the performance of the same movements (see Olshansky et al., 2015; Park et al., 2015).

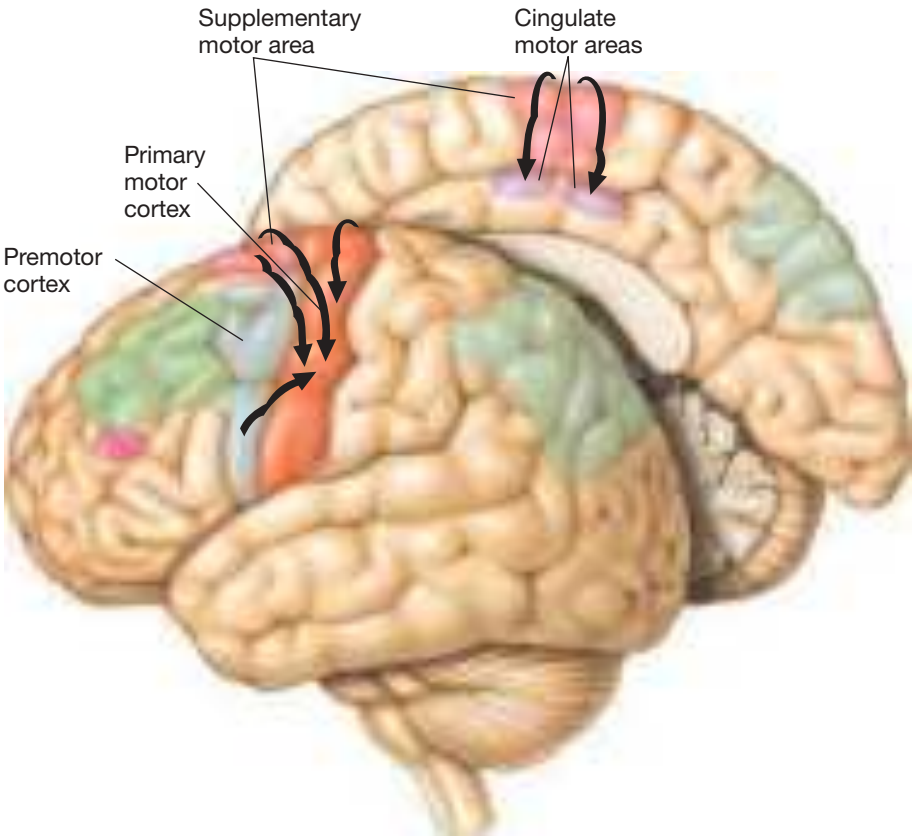
Mirror Neurons

LO 8.8 **Describe the major features of mirror neurons and explain why they have received so much attention from neuroscientists.**

Few discoveries have captured the interest of neuroscientists as much as the discovery of mirror neurons (see Rizzolatti & Fogassi, 2014). **Mirror neurons** are neurons that fire when an individual performs a particular goal-directed movement or when they observe the same goal-directed movement performed by another.

Mirror neurons were discovered in the early 1990s in the laboratory of Giacomo Rizzolatti (see Ferrari & Rizzolatti, 2014). Rizzolatti and his colleagues had been studying a class of macaque monkey ventral-premotor-area neurons that seemed to encode for particular goal objects;

Figure 8.4 Three sorts of secondary motor cortex—supplementary motor area, premotor cortex, and cingulate motor areas—and their output to the primary motor cortex. Shown are the lateral surface of the left hemisphere and the medial surface of the right hemisphere.

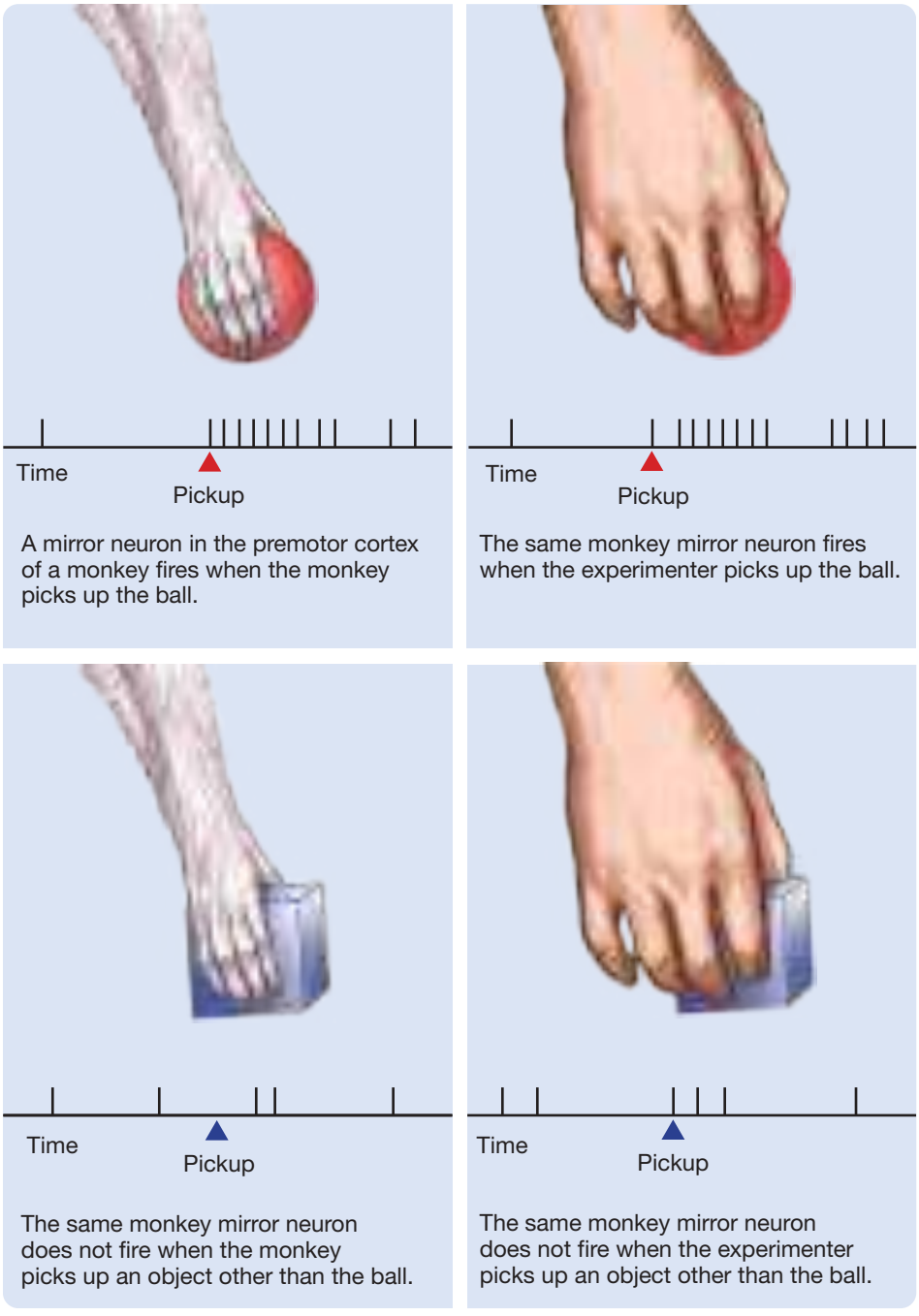


that is, these neurons fired when the monkey reached for one object (e.g., a specific toy) but not when the monkey reached for another. Then, they noticed something strange: Some of these neurons, later termed *mirror neurons*, fired just as robustly when the monkey watched the experimenter pick up the same object but not others—see Figure 8.5.

Why did the discovery of mirror neurons in the ventral premotor area create such a stir? The reason is that they provide a possible mechanism for *social cognition* (knowledge of the perceptions, ideas, and intentions of others). Mapping the actions of others onto one's own action repertoire might facilitate social understanding, cooperation, and imitation (see Farina, Borgnis, & Pozzo, 2020; Rizzolatti & Sinigaglia, 2016; Wood et al., 2016; but see Fitch, 2017; Kennedy-Constantini, 2017).

Support for the idea that mirror neurons play a role in social cognition has come from demonstrations that these neurons respond to the *understanding* of the purpose of an action, not to some superficial characteristic of the action itself (Rizzolatti & Sinigaglia, 2016; but see Churchland, 2014). For example, mirror neurons that reacted to the sight of an action that made a sound (e.g., cracking a peanut) were found to respond just as robustly to the sound alone—in other words, they responded fully to the particular action and its goal regardless of how it was detected. Indeed, many ventral premotor mirror neurons fire even when a monkey does not perceive the key action but just creates a mental representation of it.

Figure 8.5 Responses of a mirror neuron of a monkey.



Mirror neurons have been found in several areas of the macaque monkey frontal and parietal cortex (see Bonini & Ferrari, 2011; Giese & Rizzolatti, 2015). However, despite more than 600 published studies of "mirror systems" in humans, descriptions of individual mirror neurons in humans are rare (see Molenberghs, Cunnington, & Mattingley, 2012). Indeed, we know of only one: Mukamel and colleagues (2010). This is because there are few opportunities to record the firing of individual neurons in humans while conducting the required behavioral tests.

Most of the research on human mirror neuron mechanisms have been functional MRI studies. Many of these studies have found areas of human motor cortex that are active when a person performs, watches, or imagines a particular action (e.g., Farina, Borgnis, & Pozzo, 2020; Rizzolatti & Sinigaglia, 2016; Vogeley, 2017). There is no direct evidence that mirror neurons are responsible for these human findings—it is possible that different neurons in the same cortical areas contribute to the functional

MRI activity in these different conditions. However, the mirror mechanisms identified by functional MRI in humans tend to be in the same areas of cortex as those identified by single cell recording in macaques (Molenberghs et al., 2012).

Primary Motor Cortex

The **primary motor cortex** is located in the *precentral gyrus* of the frontal lobe (see Figures 8.3, 8.4, and 8.6). It is the major point of convergence of cortical sensorimotor signals, and it is the major, but not the only, point of departure of sensorimotor signals from the cerebral cortex. Understanding of the function of primary motor cortex has undergone radical changes over the past two decades—see Graziano (2016). The following two sections describe these changes.

Conventional View of Primary Motor Cortex Function

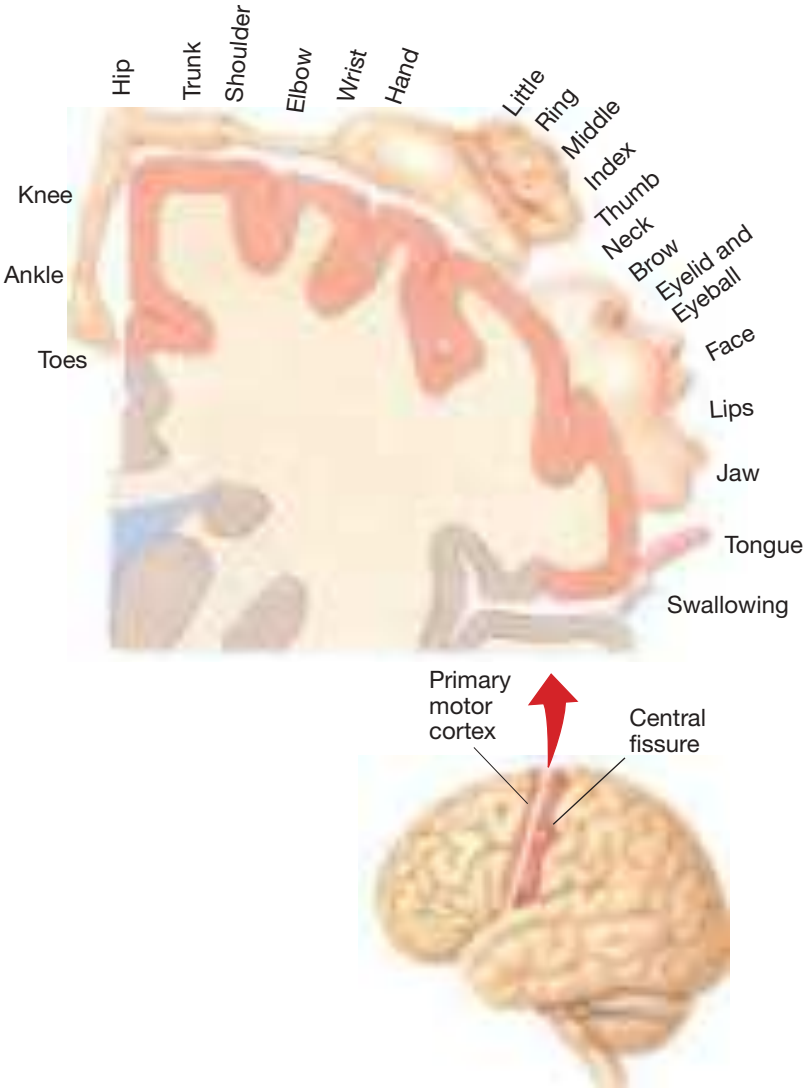
LO 8.9 **Describe the conventional view of primary motor cortex function and the evidence upon which it was based.**

In 1937, Penfield and Boldrey mapped the primary motor cortex of conscious human patients during neurosurgery by applying brief, low-intensity electrical stimulations to various points on the cortical surface and noting which part of the body moved in response to each stimulation. They found that the stimulation of each particular cortical site activated a particular contralateral muscle and produced a simple movement. When they mapped out the relation between each cortical site and the muscle that was activated by its stimulation, they found that the primary motor cortex is organized somatotopically—that is, according to a map of the body. The **somatotopic** layout of the human primary motor cortex is commonly referred to as the **motor homunculus** (see Figure 8.6). Notice that most of the primary motor cortex is dedicated to controlling parts of the body that are capable of intricate movements, such as the hands and mouth.

It is important to appreciate that each site in the primary motor cortex receives sensory feedback from receptors in the muscles and joints that the site influences. One interesting exception to this general pattern of feedback has been described in monkeys: Monkeys have at least two different hand areas in the primary motor cortex of each hemisphere, and one receives input from receptors in the skin rather than from receptors in the muscles and joints. Presumably, this latter adaptation facilitates **stereognosis**—the process of identifying objects by touch. Close your eyes and explore an object with your hands; notice how stereognosis depends on a complex interplay between motor responses and the somatosensory stimulation produced by them (see Kappers, 2011).

What is the function of each primary motor cortex neuron? Until recently, each neuron was thought to encode the direction of movement. The main evidence for this was the finding that each neuron in the arm area of the primary motor cortex fires maximally when the arm reaches in a particular direction and that each neuron has a different preferred direction.

Figure 8.6 The motor homunculus: the somatotopic map of the human primary motor cortex. Electrical stimulation of various sites in the primary motor cortex elicits simple movements in the indicated parts of the body.



Based on Penfield, W., & Rasmussen, T. (1950). *The cerebral cortex of man: a clinical study of the localization of function*. New York, NY: Macmillan.

Current View of Primary Motor Cortex Function

LO 8.10 Describe the current view of primary motor cortex function and the evidence upon which it is based.

Recent efforts to map the primary motor cortex have used a new stimulation technique—see Graziano (2016). Rather than stimulating with brief pulses of current that are just above the threshold to produce a reaction, investigators have used longer bursts of current (e.g., 0.5 to 1 seconds; see Van Acker et al., 2014), which are more similar to the duration of a motor response. The results were amazing: Rather than eliciting the contractions of individual muscles, these currents elicited complex natural-looking response sequences. For example, stimulation at one site reliably produced a feeding response: The arm reached forward, the hand closed as if clasping some food, the closed hand was brought to the mouth, and finally the mouth opened. These recent studies have revealed a looser somatotopic organization than was previously thought. For example, although stimulations to the face area do tend to elicit facial movements, those movements are complex species-typical movements (e.g., an aggressive facial expression) rather than individual muscle contractions (see Ejaz, Hamada, & Diedrichsen, 2015). Also, sites that move a particular body part overlap greatly with sites that move other body parts (Sanes et al., 1995). Presumably that is why small lesions in the hand area of the primary motor cortex of humans (Scheiber, 1999) or monkeys (Scheiber & Poliakov, 1998) do not selectively disrupt the activity of a single finger.

The conventional view that many primary motor cortex neurons are tuned to movement in a particular direction has also been challenged. In the many studies that have supported this conventional view, the monkey subjects were trained to make arm movements from a central starting point so that the relation between neural firing and the direction of movement could be precisely assessed. In each case, each neuron fired only when the movements were made at a particular angle. However, an alternative to the idea that motor neurons are coded to particular angles of movement has come from the findings of studies in which the activity of individual primary motor cortex neurons is recorded as monkeys moved about freely (see Graziano, 2016; Harrison & Murphy, 2014)—rather than as they performed simple, learned arm movements from a set starting point. The firing of many primary motor cortex neurons in freely moving monkeys was often related to the particular end point of a movement, not to the direction of the movement. That is, if a monkey reached toward a particular location, primary motor cortex neurons sensitive to that target location tended to become active regardless of the direction of the movement that was needed to get from the starting point to the target.

The importance of the target of a movement, rather than the direction of a movement, for the function of primary motor cortex was also apparent in stimulation studies (see Graziano, 2016; Harrison & Murphy, 2014). For example, if stimulation of a particular motor cortex site caused a straight arm to bend at the elbow to a 90-degree angle, stimulation of the same site caused a tightly bent arm (i.e., bent past 90 degrees towards the animal's body) to straighten to the same 90-degree angle. In other words, the same stimulation of motor cortex can produce opposite movements depending on the starting position, but the end position of the movements remains the same. Stop for a moment and consider the implications of this finding—they are as important as they are counterintuitive. First, the finding means that the signals from every site in the primary motor cortex diverge greatly, so each particular site has the ability to get a body part (e.g., an arm) to a target location regardless of the starting position. Second, it means that the sensorimotor system is inherently plastic. Apparently, each location in the primary motor cortex can produce the innumerable patterns of muscle contraction and relaxation (Davidson et al., 2007) required to get a body part from any starting point to a specific target location. Accordingly, it has been suggested that the primary motor cortex contains an **action map** (see Graziano, 2016) in addition to a topographic map.

The neurons of the primary motor cortex play a major role in initiating body movements. With an appropriate interface, could they control the movements of a machine (see Georgopoulos & Carpenter, 2015)? Belle says, "Yes."

Belle: The Monkey That Controlled a Robot with Her Mind

In the laboratory of Miguel Nicolelis and John Chapin, a tiny owl monkey called Belle watched a series of lights on a control panel. Belle had learned that if she moved the joystick in her right hand in the direction of a light, she would be rewarded with a drop of fruit juice. On this particular day, as a light flashed on the panel, 100 microelectrodes recorded extracellular unit activity from neurons in Belle's primary motor cortex. This activity moved Belle's arm toward the light, but at the same time, the signals were analyzed by a computer, which fed the output to a laboratory several hundred kilometers away, at the Massachusetts Institute of Technology. At MIT, the signals from Belle's brain entered the circuits of a robotic arm. On each trial, the activity of Belle's primary motor cortex moved her arm toward the test light, and it moved the robotic arm in the same direction. Belle's neural signals were directing the activity of a robot.

Belle's remarkable feat raised a possibility that is starting to be realized. Indeed, there has been a recent flurry of technological advances involving *brain–computer interfaces* (i.e., direct communication between a computer and the

brain—usually via an array of electrodes placed in the brain). For example, paralyzed patients have learned to control robotic arms with neural signals collected via multi-electrode arrays implanted in the primary motor cortex (Collinger et al., 2013; Golub et al., 2016; Pruszynski & Diedrichsen, 2015).

Brain-computer interfaces have also been used to mitigate the effects of spinal-cord damage. For example, in a study by Capogrosso and colleagues (2016), monkeys with transected spinal cords each had a wireless transmitter implanted in their motor cortex to record and transmit motor cortex activity. Another wireless receiver positioned on their spinal cord just below the site of transection converted that transmitted message into a pattern of stimulation that elicited movement of their paralyzed limb (Capogrosso et al., 2016). Such *brain–spine-computer interfaces* might someday allow for significant recovery from the effects of spinal cord damage (see Jackson, 2016).

EFFECTS OF PRIMARY MOTOR CORTEX LESIONS. Extensive damage to the human primary motor cortex has less effect than you might expect, given that this cortex is the major point of departure of motor fibers from the cerebral cortex. Large lesions to the primary motor cortex may disrupt a patient's ability to move one body part (e.g., one finger) independently of others (see Ebbesen & Brecht, 2017), may produce **astereognosia** (deficits in stereognosis), and may reduce the speed, accuracy, and force of a patient's movements. Such lesions do not, however, eliminate voluntary movement, presumably because there are parallel pathways that descend directly from secondary and association motor areas to subcortical motor circuits without passing through primary motor cortex.

Cerebellum and Basal Ganglia

The cerebellum and the basal ganglia (see Figures 3.20 and 3.28) are both important and highly interconnected sensorimotor structures (see Bostan & Strick, 2018), but neither is a major part of the pathway by which signals descend through the sensorimotor hierarchy. Instead, both the cerebellum and the basal ganglia interact with different levels of the sensorimotor hierarchy and, in so doing, coordinate and modulate its activities.

Cerebellum

LO 8.11 Describe the structure and connectivity of the cerebellum and explain the current view of cerebellar function.

The cerebellum's structure and complex connectivity with other brain structures suggest its functional complexity (see Bostan & Strick, 2018; Buckner, 2013). And while it constitutes only 10 percent of the mass of the brain, the cerebellum contains more than half of the brain's neurons (Azevedo et al., 2009).

The cerebellum receives information from primary and secondary motor cortex, information about descending motor signals from brain-stem motor nuclei, and feedback from motor responses via the somatosensory and vestibular systems. The cerebellum is thought to compare these three sources of input and correct ongoing movements that deviate from their intended course (see Bastian, 2006; Bell, Han, & Sawtell, 2008; Herzfeld & Shadmehr, 2014). By performing this function, it is believed to play a major role in motor learning, particularly in the learning of sequences of movements in which timing is a critical factor (see Pritchett & Carey, 2014).

The effects of diffuse cerebellar damage on motor function are devastating. The patient loses the ability to accurately control the direction, force, velocity, and amplitude of movements and the ability to adapt patterns of motor output to changing conditions. It is particularly difficult to maintain steady postures (e.g., standing), and attempts to do so frequently lead to tremor. There are also severe disturbances in balance, gait, speech, and the control of eye movement. Learning new motor sequences is difficult (Thach & Bastian, 2004). These effects of cerebellar damage suggest that the cerebellum plays a major role in monitoring and adapting ongoing patterns of movement (see Peterburs & Desmond, 2016)

The functions of the cerebellum were once thought to be entirely sensorimotor, but this conventional view is no longer tenable (see Buckner, 2013; Koziol et al., 2014). Patients with cerebellar damage often display diverse sensory, cognitive, emotional, and memory deficits (see Sokolov, Miall, & Ivry, 2017). Also, healthy volunteers often display cerebellar activity during sensory, cognitive, or emotional activities. There are several competing theories of cerebellar function (see Koziol et al., 2014), but a popular one is that the cerebellum plays an important role in learning from one's errors and in the prediction of errors (see Herzfeld et al., 2018; Sokolov, Miall, & Ivry, 2017).

Basal Ganglia

LO 8.12 Describe the anatomy of the basal ganglia and explain the current view of their function.

The basal ganglia do not contain as many neurons as the cerebellum, but in one sense they are more complex. Unlike the cerebellum, which is organized systematically in lobes, columns, and layers, the basal ganglia are a complex heterogeneous collection of interconnected nuclei.

The anatomy of the basal ganglia suggests that, like the cerebellum, they perform a modulatory function (see Nelson & Kreitzer, 2014). They contribute few fibers to

descending motor pathways; instead, they form neural loops via their numerous reciprocal connections with cortical areas and the cerebellum (Bostan & Strick, 2018; Nelson & Kreitzer, 2014; Oldenburg & Sabatini, 2015). Many of the cortical loops carry signals to and from the motor areas of the cortex (see Nambu, 2008).

Theories of basal ganglia function have changed in much the same way that theories of cerebellar function have changed. The traditional view of the basal ganglia was that they, like the cerebellum, play a role in the modulation of motor output. Now, the basal ganglia are thought to also be involved in a variety of cognitive functions (see Eisinger et al., 2018; Hikosaka et al., 2014; Lim, Fiez, & Holt, 2014; Rektor et al., 2015) and in many aspects of motivation (see Bostan & Strick, 2018). The basal ganglia have also been shown to participate in learning. For example, they play a role in *habit learning*, a type of learning that is usually acquired gradually, trial-by-trial (see Ashby, Turner, & Horovitz, 2010), and in classical conditioning (see Stephenson-Jones et al., 2016).

One theory of basal ganglia sensorimotor function is based on its known roles in both movement and motivation (see Averbeck & Costa, 2017; Schultz, 2016). This theory comprises two major assertions. The first states that the basal ganglia are responsible for **movement vigor** (see Dudman & Kraukauer, 2016): the control of the speed and amplitude of movement based on motivational factors. For example, the basal ganglia might enable a concert pianist to play a particular piece with more or less vigor. The second assertion is that movement not only involves the execution of actions but also requires that we actively suppress motor activity that would otherwise be inappropriate or unhealthy. For example, we have to suppress our tendency to display inappropriate yawning or scratching at social gatherings; we also need to suppress unwanted movements generated by the ongoing spontaneous activity of our muscles (e.g., tremor, twitching, coughing). When such movement inhibition fails, symptoms of a neurological or psychiatric disorder can emerge (see Duque et al., 2017).

Scan Your Brain

Now that you have learned about the sensorimotor pathways, this is a good place for you to pause to scan your brain to evaluate your knowledge by completing the following statements. The correct answers are provided at the end of the exercise. Before proceeding, review material related to your incorrect answers and omissions.

1. The _____ _____ association cortex provides important spatial information and helps direct attention to external stimuli.
2. _____ movements are normally not affected by sensory feedback.
3. Motor learning, such as riding a bike, begins with responses under conscious control, but with practice these are adjusted by _____ feedback without conscious regulation.
4. _____ is a disorder of voluntary movement that cannot be explained by paralysis; rather, it is attributed to the inability to perform motor movements when instructed to do so.
5. _____ _____, a striking consequence of posterior parietal cortex damage, is a disturbance of a patient's ability to respond to stimuli on the side of the body opposite to the side of a brain lesion in the absence of simple sensory or motor deficits.
6. The supplementary motor area and premotor cortex are part of the _____ _____ cortex that is involved in programming patterns of movements.
7. _____ are neurons that fire when an individual performs a particular goal-directed hand movement or when they observe the same goal-directed movement performed by another.
8. The somatotopic layout of the human primary cortex is also known as the _____ _____.
9. The _____ is involved in motor learning and the temporal association of motor actions. As such, damage to this area can cause detrimental effects on posture, gait, speech, and balance.
10. Recent views of the function of the basal ganglia suggest that they are involved in various cognitive functions including _____ learning.

Scan Your Brain answers: (1) posterior parietal, (2) Ballistic, (3) sensory, (4) Apraxia, (5) Contralateral neglect, (6) secondary motor, (7) Mirror neurons, (8) motor homunculus, (9) cerebellum, (10) habit.

Descending Motor Pathways

Neural signals are conducted from the primary motor cortex to the motor neurons of the spinal cord over four different pathways. Two pathways descend in the *dorsolateral* region of the spinal cord—collectively known as the *dorsolateral motor pathways*, and two descend in the *ventromedial* region of the spinal cord—collectively known as the *ventromedial motor pathways*. Signals conducted over these pathways act together in the control of voluntary movement (see Iwaniuk & Whishaw, 2000). Like a large company, the sensorimotor system does not work well unless there are good lines of communication from the executive level (the cortex) to the office personnel (the spinal motor circuits) and workers (the muscles).

The Two Dorsolateral Motor Pathways and the Two Ventromedial Motor Pathways

LO 8.13 Compare and contrast the two dorsolateral motor pathways and the two ventromedial motor pathways.

The descending dorsolateral and ventromedial motor pathways are similar in that each is composed of two major tracts, one whose axons descend directly to the spinal cord and another whose axons synapse in the brain stem on neurons that in turn descend to the spinal cord. However, the *dorsolateral tracts* differ from the *ventromedial tracts* in two major respects:

- The ventromedial tracts are much more diffuse. Many of their axons innervate interneurons on both sides of the spinal gray matter and in several different segments, whereas the axons of the dorsolateral tracts terminate in the contralateral half of one spinal cord segment, sometimes directly on a motor neuron.
- The motor neurons activated by the ventromedial tracts project to proximal muscles of the trunk and limbs (e.g., shoulder muscles), whereas the motor neurons activated by the dorsolateral tracts project to distal muscles (e.g., finger muscles).

Because all four of the descending motor tracts originate in the cerebral cortex, all are presumed to mediate voluntary movement; however, major differences in their routes and destinations suggest that they have different functions. This difference was first demonstrated in an experiment on monkeys by Lawrence and Kuypers.

In their experiment, Lawrence and Kuypers (1968) made complete transections of the dorsolateral tracts in monkeys. The monkeys could stand, walk, and climb after this transection, but when they were sitting, their arms hung limply by their sides (remember that monkeys normally use their arms for standing and walking). In those few instances in which the monkeys did use an arm for reaching, they used it like a rubber-handled rake—throwing it out from the shoulder and using it to draw small objects of interest back along the floor.

The other group of monkeys in their experiment had complete transections of their ventromedial tracts. In contrast to the first group, these subjects had severe postural abnormalities: They had great difficulty walking or sitting. If they did manage to sit or stand without clinging to the bars of their cages, the slightest disturbance, such as a loud noise, frequently made them fall.

What do these experiments tell us about the roles of the various descending sensorimotor tracts in the control of primate movement? They suggest that the ventromedial tracts are involved in the control of posture and whole-body movements (e.g., walking, climbing) and that they can exert control over the limb movements involved in such activities. In contrast, the dorsolateral tracts control the movements of the limbs (see Ruder & Arber, 2019).

Sensorimotor Spinal Circuits

We have descended the sensorimotor hierarchy to its lowest level: the spinal circuits and the muscles they control. Psychologists, including us, tend to be brain-oriented, and they often think of the spinal cord motor circuits as mere cables that carry instructions from the brain to the muscles. If you think this way, you will be surprised: The motor circuits of the spinal cord show considerable complexity in their functioning, independent of signals from the brain (see Dasen, 2017; Giszter, 2015; Kiehn, 2016; Ruder & Arber, 2019). Again, the business metaphor helps put this in perspective: Can the office managers (spinal circuits) and workers (muscles) of a company function effectively when all of the executives are at a convention in Hawaii? Of course they can.

Muscles

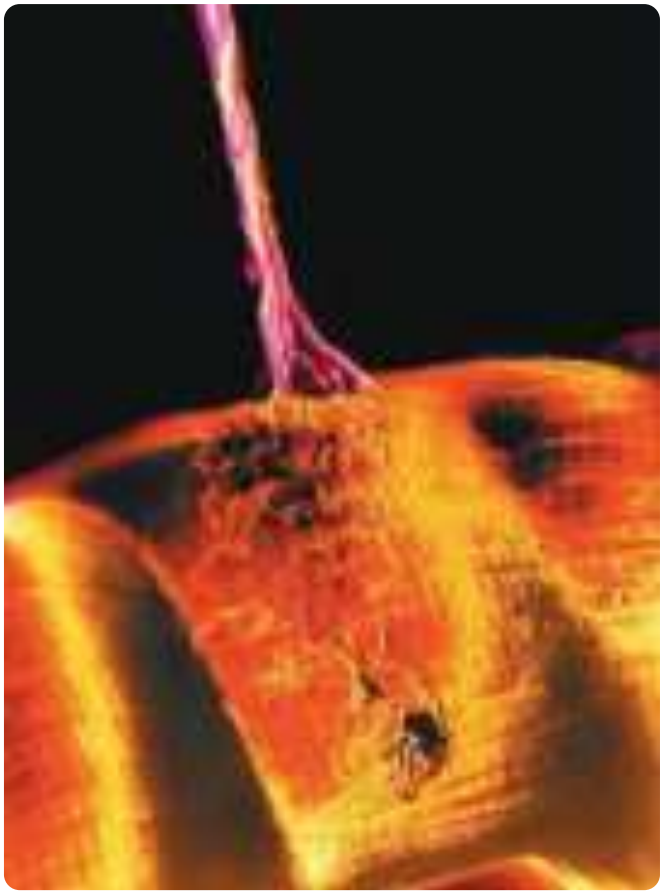
LO 8.14 Describe the components of a motor unit and distinguish between the different types of muscles.

Motor units are the smallest units of motor activity. Each motor unit comprises a single motor neuron and all of the individual skeletal muscle fibers that it innervates (see Figure 8.7). When the motor neuron fires, all the muscle fibers of its unit contract together. Motor units differ appreciably in the number of muscle fibers they contain; the units with the fewest fibers—those of the fingers and face—permit the highest degree of selective motor control.

A skeletal muscle comprises hundreds of thousands of threadlike muscle fibers bound together in a tough membrane and attached to a bone by a *tendon*. *Acetylcholine*, which is released by motor neurons at *neuromuscular junctions*, activates the **motor end-plate** on each muscle fiber and causes the fiber to contract. Contraction is the only method that muscles have for generating force, thus, any muscle can generate force in only one direction. All of the motor neurons that innervate the fibers of a single muscle are called its **motor pool**.

Although it is an oversimplification (see Gollnick & Hodgson, 1986), skeletal muscle fibers are often considered to be of two basic types: fast and slow. *Fast muscle fibers*, as you might guess, are those that contract and relax quickly. Although they are capable of generating great force, they fatigue quickly because they are *poorly vascularized* (have few blood vessels, which gives them a pale color). In contrast, *slow muscle fibers*, although slower and weaker, are

Figure 8.7 An electron micrograph of a motor unit: a motor neuron (pink) and the muscle fibers it innervates.



CNRI/Science Source

capable of more sustained contraction because they are more richly vascularized (and hence much redder). Each muscle has both fast and slow fibers—the fast muscle fibers participate in quick movements such as jumping, whereas the slow muscle fibers participate in gradual movements such as walking. Because each muscle can apply force in only one direction, joints that move in more than one direction must be controlled by more than one muscle. Many skeletal muscles belong unambiguously to one of two categories: flexors or extensors. **Flexors** act to bend or flex a joint, and **extensors** act to straighten or extend it. Figure 8.8 illustrates the *biceps* and *triceps*—the flexor and extensor, respectively, of the elbow joint. Any two muscles whose contraction produces the same movement, be it flexion or extension, are said to be **synergistic muscles**; those that act in opposition, like the biceps and the triceps, are said to be **antagonistic muscles**.

To understand how muscles work, it is important to realize that they are elastic, rather than inflexible and cablelike. If you think of an increase in muscle tension as analogous to an increase in the tension of an elastic band joining two bones, you will appreciate that muscle contraction can be of two types. Activation of a muscle can increase the tension that it exerts on two bones without shortening and pulling them together; this is termed **isometric contraction**. Or it can shorten and pull them together; this is termed **dynamic contraction**. The tension in a muscle can be increased by increasing the number of neurons in its motor pool that are firing, by increasing the firing rates of those already firing, or more commonly by a combination of these two changes.

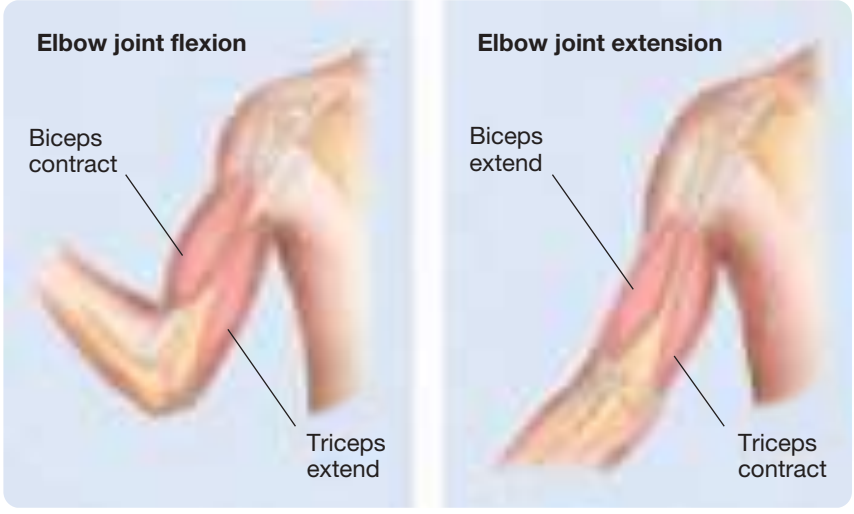
Receptor Organs of Tendons and Muscles

LO 8.15 Describe the receptor organs of tendons and muscles.

The activity of skeletal muscles is monitored by two kinds of receptors: Golgi tendon organs and muscle spindles. **Golgi tendon organs** are embedded in the *tendons*, which connect each skeletal muscle to bone; **muscle spindles** are embedded in the muscle tissue itself. Because of their different locations, Golgi tendon organs and muscle spindles respond to different aspects of muscle contraction. Golgi tendon organs respond to increases in muscle tension (i.e., to the pull of the muscle on the tendon), but they are completely insensitive to changes in muscle length. In contrast, muscle spindles respond to changes in muscle length, but they do not respond to changes in muscle tension.

Under normal conditions, the function of Golgi tendon organs is to provide the central nervous system with

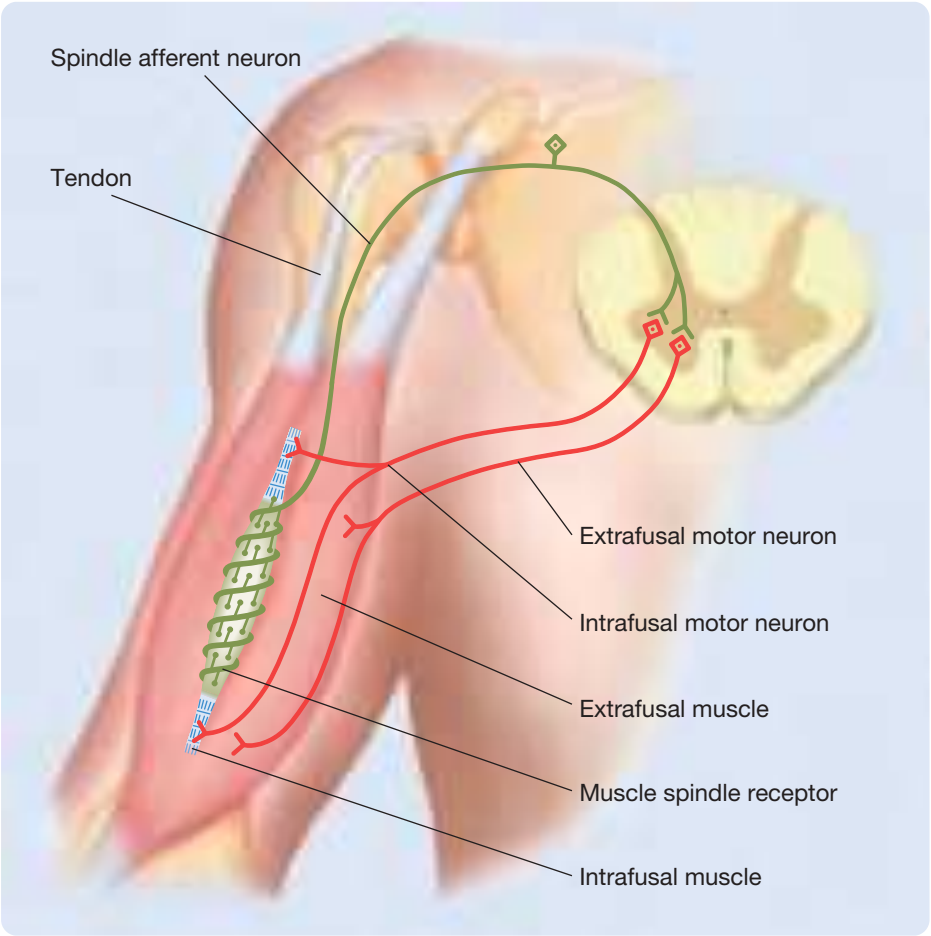
Figure 8.8 The biceps and triceps, which are the flexor and extensor muscles, respectively, of the elbow joint.



information about muscle tension, but they also serve a protective function. When the contraction of a muscle is so extreme that there is a risk of damage, the Golgi tendon organs excite inhibitory interneurons in the spinal cord that cause the muscle to relax.

Figure 8.9 is a schematic diagram of the *muscle-spindle feedback circuit*. Examine it carefully. Notice that each muscle spindle has its own threadlike **intrafusal muscle**, which is innervated by its own **intrafusal motor neuron**. Why would a receptor have its own muscle and motor neuron? The reason becomes apparent when you consider what would happen to a muscle spindle without them. Without its intrafusal motor input, a muscle spindle would fall slack each time its **skeletal muscle (extrafusal muscle)** contracted. In this slack state, the muscle spindle could not do its job, which is to respond to slight changes in extrafusal muscle length. As Figure 8.10 illustrates, the intrafusal motor neuron solves this problem by shortening the intrafusal muscle each time the extrafusal muscle becomes shorter, thus keeping enough tension on the middle, stretch-sensitive portion of the muscle spindle to keep it responsive to slight changes in the length of the extrafusal muscle.

Figure 8.9 The muscle-spindle feedback circuit. There are many muscle spindles in each muscle; for clarity, only one much-enlarged muscle spindle is illustrated here.



Stretch Reflex

LO 8.16 Describe the stretch reflex and explain its mechanism.

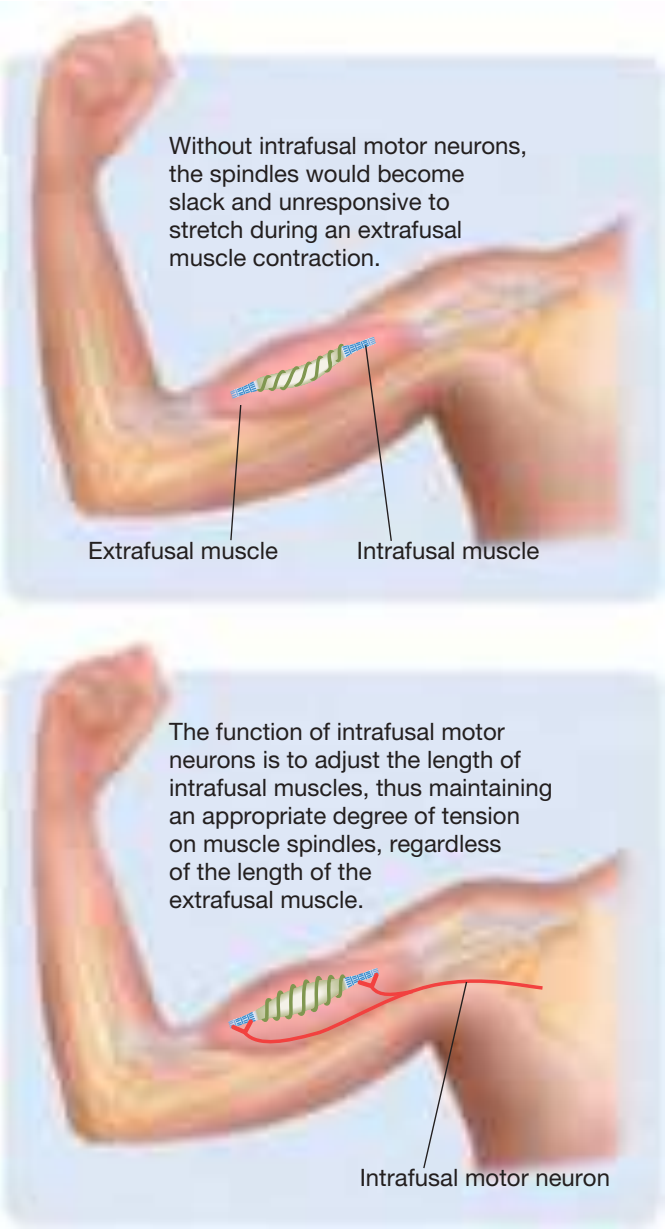
When the word *reflex* is mentioned, many people think of themselves sitting on the edge of their doctor's examination table having their knees rapped with a little rubber-headed hammer. The resulting leg extension is called the **patellar tendon reflex** (*patella* means "knee"). This reflex is a **stretch reflex**—a reflex elicited by a sudden external stretching force on a muscle.

When your doctor strikes the tendon of your knee, the extensor muscle running along your thigh is stretched. This initiates the chain of events depicted in Figure 8.11. The sudden stretch of the thigh muscle stretches its muscle-spindle stretch receptors, which in turn initiate a volley of action potentials carried from the stretch receptors into the spinal cord by **spindle afferent neurons** via the *dorsal root*. This volley of action potentials excites motor neurons in the *ventral horn* of the spinal cord, which respond by sending action potentials back to the muscle whose stretch originally excited them (see Illert & Kummel, 1999). The arrival of these impulses back at the starting point results in a compensatory muscle contraction and a sudden leg extension.

The method by which the patellar tendon reflex is typically elicited in a doctor's office—that is, by a sharp blow to the tendon of a completely relaxed muscle—is designed to make the reflex readily observable. However, it does little to communicate its functional significance. In real-life situations, the function of the stretch reflex is to keep external forces from altering the intended position of the body. When an external force, such as a push on your arm while you are holding a cup of coffee, causes an unanticipated extrafusal muscle stretch, the muscle-spindle feedback circuit produces an immediate compensatory contraction of the muscle that counteracts the force and keeps you from spilling the coffee—unless, of course, you are wearing your best clothes.

The mechanism by which the stretch reflex maintains limb

Figure 8.10 The function of intrafusal motor neurons.



stability is illustrated in Figure 8.12. Examine it carefully because it illustrates two of the principles of sensorimotor system function that are the focus of this chapter: the important role played by sensory feedback in the regulation of motor output and the ability of lower circuits in the motor hierarchy to take care of "business details" without the involvement of higher levels.

Withdrawal Reflex

LO 8.17 Describe the withdrawal reflex and explain its mechanism.

We are sure that, at one time or another, you have touched something painful—a hot pot, for example—and suddenly pulled back your hand. This is a **withdrawal reflex**. Unlike the stretch reflex, the withdrawal reflex is *not monosynaptic*. When a painful stimulus is applied to the hand, the first responses are recorded in the motor neurons of the arm flexor muscles about 1.6 milliseconds later, about the time it takes a neural signal to cross two synapses. Thus, the shortest route in the withdrawal-reflex circuit involves one interneuron. Other responses are recorded in the motor neurons of the arm flexor muscles after the initial volley; these responses are triggered by signals that have traveled over multisynaptic pathways—some involving the cortex. See Figure 8.13.

Reciprocal Innervation

LO 8.18 Explain what is meant by *reciprocal innervation*.

Reciprocal innervation is an important principle of spinal cord circuitry. It refers to the fact that antagonistic muscles

Figure 8.11 The elicitation of a stretch reflex. All of the muscle spindles in a muscle are activated during a stretch reflex, but only a single muscle spindle is depicted here.

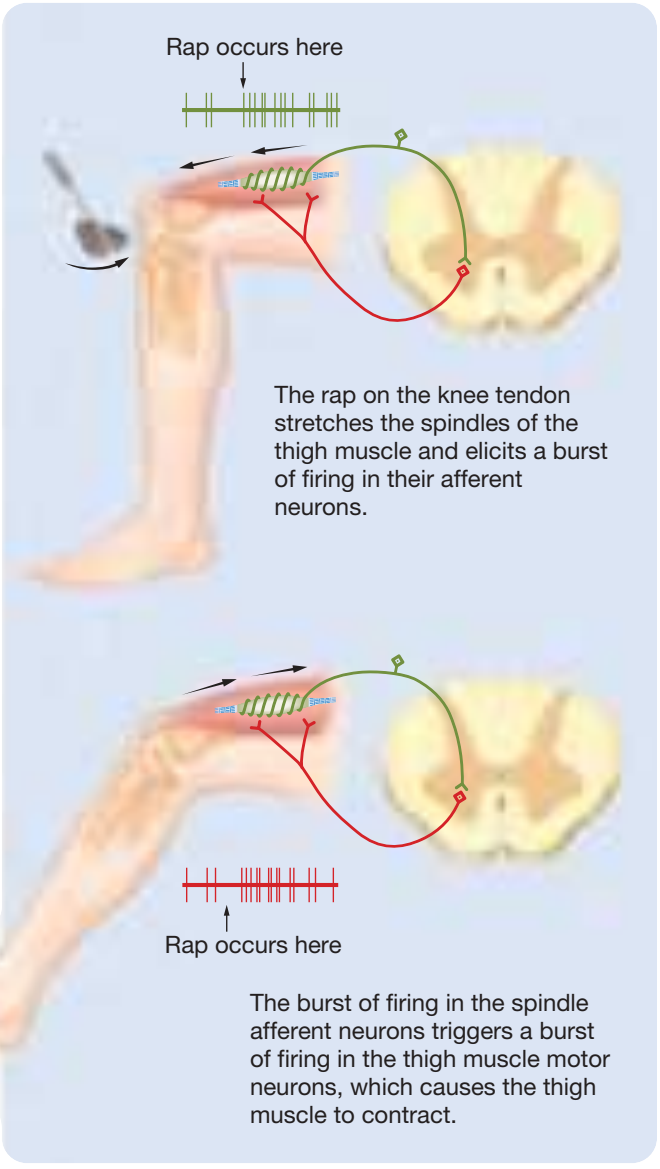
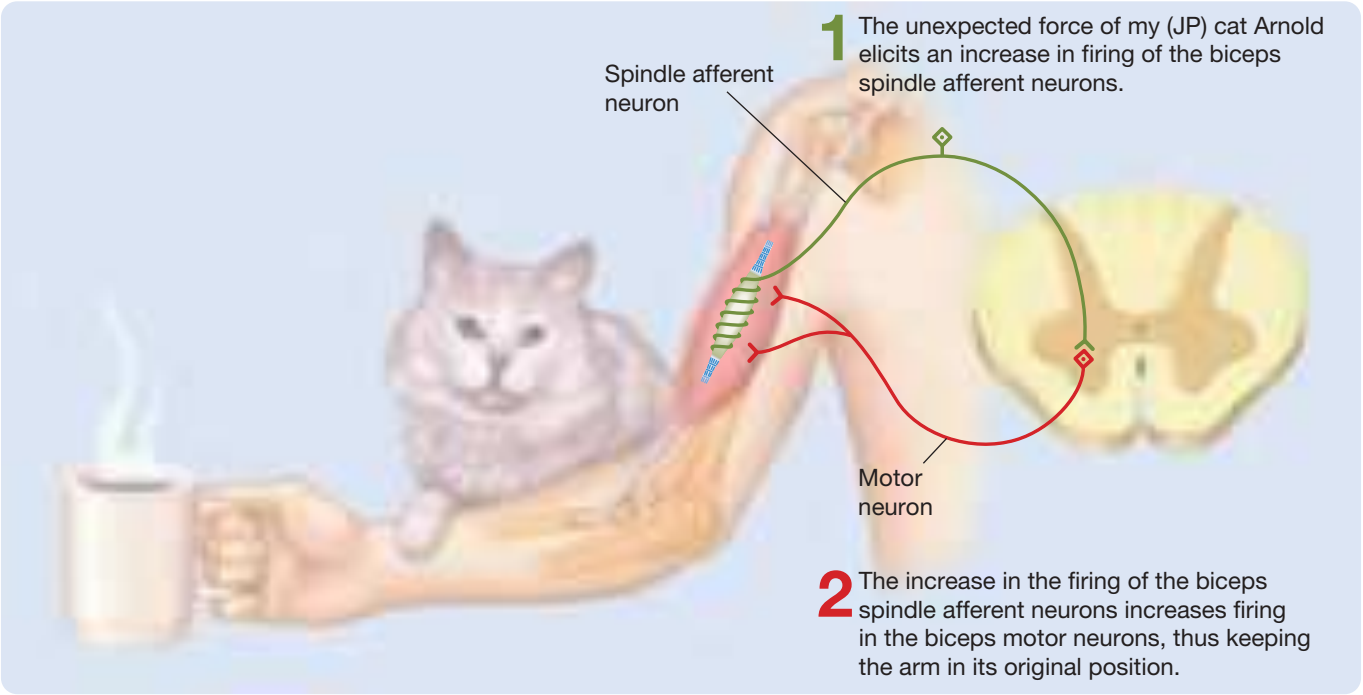
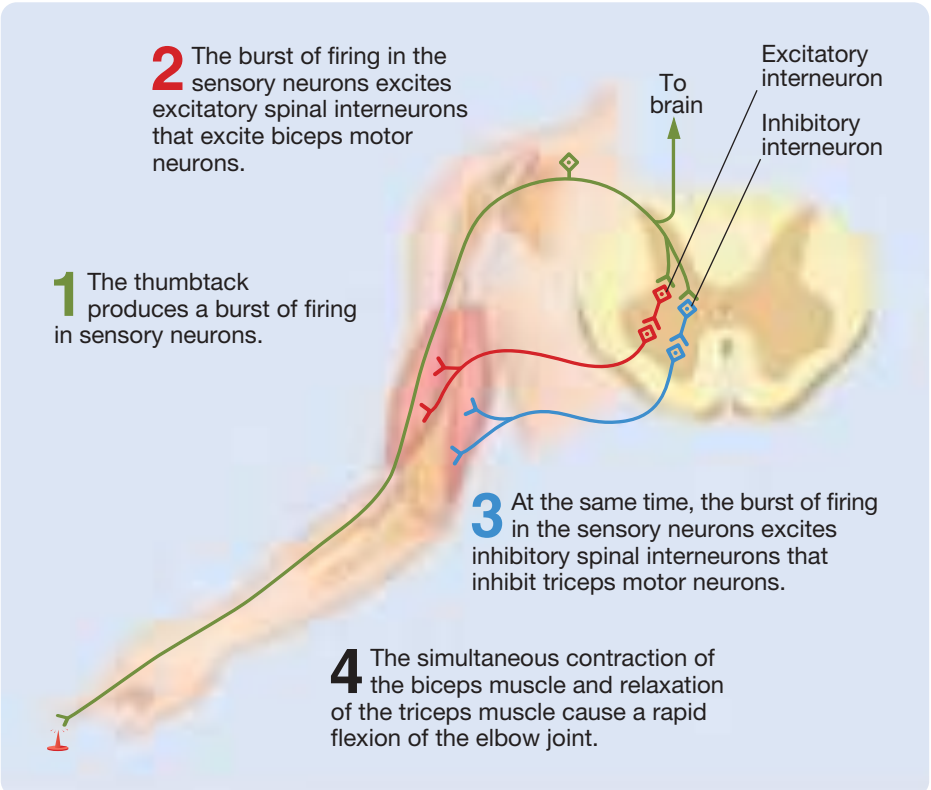


Figure 8.12 The automatic maintenance of limb position by the muscle-spindle feedback system.



are innervated in a way that permits a smooth, unimpeded motor response: When one is contracted, the other relaxes. Figure 8.13 illustrates the role of reciprocal innervation in the withdrawal reflex. "Bad news" of a sudden painful event in the hand arrives in the dorsal horn of the spinal cord and has two effects: The signals excite both excitatory and inhibitory interneurons. The excitatory interneurons excite the motor neurons of the elbow flexor; the inhibitory interneurons inhibit the motor neurons of the elbow extensor. Thus, a single sensory input produces a coordinated pattern of motor output; the activities of agonists and antagonists are automatically coordinated by the internal circuitry of the spinal cord (see Nielsen, 2016).

Figure 8.13 The reciprocal innervation of antagonistic muscles in the arm. During a withdrawal reflex, elbow flexors are excited, and elbow extensors are inhibited.



Movements are quickest when there is simultaneous excitation of all agonists and complete inhibition of all antagonists; however, this is not the way voluntary movement is normally produced. Most muscles are always contracted to some degree, and movements are produced by adjustment in the level of relative cocontraction between antagonists. Movements produced by **cocontraction** are smooth, and they can be stopped with precision by a slight increase in the contraction of the antagonistic muscles. Moreover, cocontraction insulates us from the effects of unexpected external forces.

Recurrent Collateral Inhibition

LO 8.19 Explain recurrent collateral inhibition.

Like most workers, muscle fibers and the motor neurons that innervate them need an occasional break, and inhibitory neurons in the spinal cord make sure they get it. Each motor neuron branches just before it leaves the spinal cord, and the branch synapses on a small inhibitory interneuron, which inhibits the very motor neuron from which it receives its input (see Illert & Kummel, 1999). The inhibition produced by these local feedback circuits is called **recurrent collateral inhibition**, and the small inhibitory interneurons that mediate recurrent collateral inhibition are called *Renshaw cells*. As a consequence of recurrent collateral inhibition, each time a motor neuron fires, it momentarily inhibits itself and shifts the responsibility for the contraction of a particular muscle to other members of the muscle's motor pool.

Figure 8.14 provides a summary; it illustrates recurrent collateral inhibition and other factors that directly excite or inhibit motor neurons.

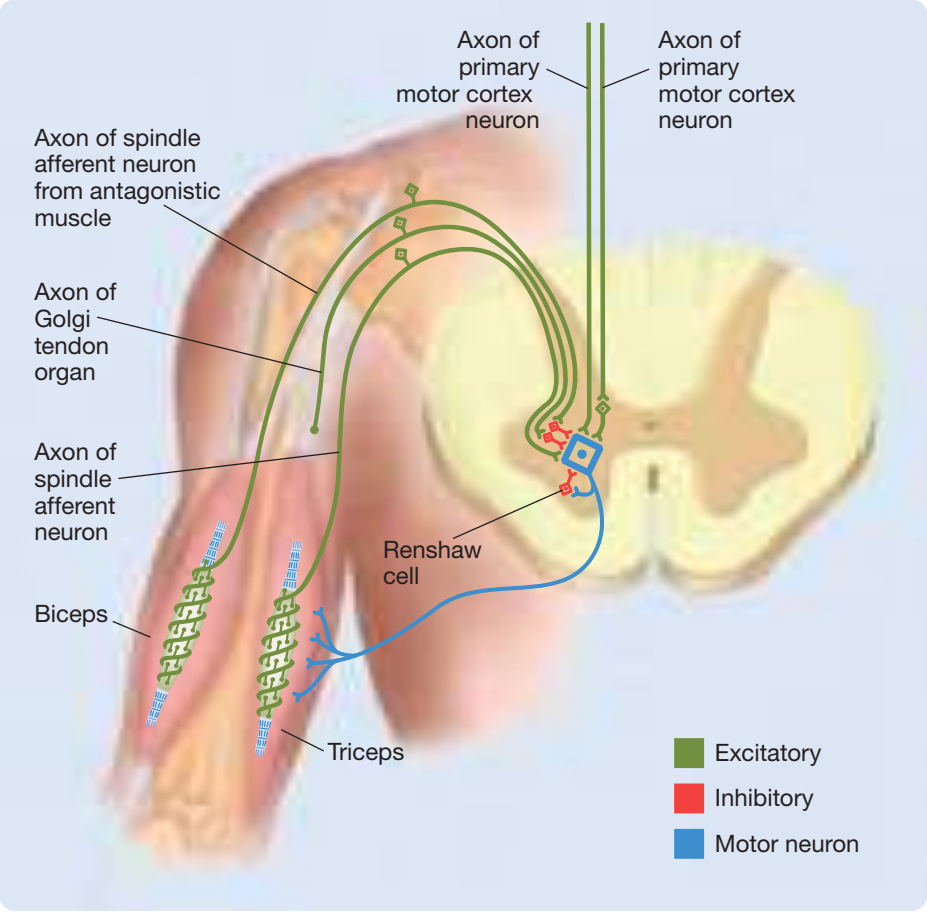
Walking: A Complex Sensorimotor Reflex

LO 8.20 Describe the phenomenon of walking and the degree to which it is controlled by spinal circuits.

Most reflexes are much more complex than withdrawal and stretch reflexes. Think for a moment about the complexity of the program of reflexes that is needed to control an activity such as walking. Such a program must integrate visual information from the eyes; somatosensory information from the feet, knees, hips, arms, and so on; information about balance from the semicircular canals of the inner ears; and information from newly discovered sensory receptors in the spinal cord that detect mechanical and chemical information from the cerebrospinal fluid in the central canal (see Böhm & Wyart, 2016). That program must produce, on the basis of all this information, an integrated series of movements that involves the muscles of the trunk, legs, feet, and upper arms. This program of reflexes must also be incredibly plastic; it must be able to adjust its output immediately to changes in the slope of the terrain, to instructions from the brain, or to sudden external forces. Remarkably, similar patterns of neural activity control walking in humans, other mammals, and birds (see Dominici et al., 2011; Grillner, 2011).

Grillner (1985) showed that the spinal cord, with no contribution whatsoever from the brain, can control walking. Grillner's subjects were cats whose spinal cords had been separated from their brains by transection. He suspended the cats in a sling over a treadmill. Amazingly, when the treadmill was started so that the cats received sensory feedback of the sort that normally accompanies walking, they began to walk. Similar results have been observed in other species (see Kiehn, 2016).

Figure 8.14 The excitatory and inhibitory signals that directly influence the activity of a motor neuron.



Journal Prompt 8.2

Why might walking have evolved in such a way that it can be controlled independent of input from the brain?

Central Sensorimotor Programs and Learning

In this chapter, you have learned that the sensorimotor system is like the hierarchy of a large efficient company. You have learned how the executives—the dorsolateral prefrontal cortex and the secondary motor cortexes—issue commands based on information supplied to them in part by the posterior parietal cortex. And you have learned how these commands are forwarded to the director of operations (the primary motor cortex) for distribution over four main channels of communication (the two dorsolateral and the two ventromedial spinal motor pathways) to the metaphoric office managers of the sensorimotor hierarchy (the spinal sensorimotor circuits). Finally, you have learned how spinal sensorimotor circuits direct the activities of the workers (the muscles).

In this final module, you will learn about central sensorimotor programs. The module concludes with revisiting the case of Rhonelle the cashier.

A Hierarchy of Central Sensorimotor Programs

LO 8.21 Explain what is meant by a hierarchy of central sensorimotor programs and explain the importance of this arrangement for sensorimotor functioning.

One view of sensorimotor function is that the sensorimotor system comprises a hierarchy of **central sensorimotor programs**. According to this view, all but the highest levels of the sensorimotor system have certain patterns of activity programmed into them, and complex movements are produced by activating the appropriate combinations of these programs. For example, if you want to look at a magazine, your association cortex will activate high-level cortical programs that in turn will activate lower-level programs—perhaps in your brain stem—for walking, bending over, picking up, and thumbing through. These programs in turn will activate spinal programs that control the various elements of the sequences and cause your muscles to complete the objective (Grillner & Jessell, 2009).

Once activated, each level of the sensorimotor system is capable of operating on the basis of current sensory feedback without the direct control of higher levels. Thus, although the highest levels of your sensorimotor system retain the option of directly controlling your activities, most of the individual responses that you make are performed without direct cortical involvement, and you are often barely aware of them (see Custers & Aarts, 2010).

In much the same way, a company president who wishes to open a new branch office simply issues the command to one of the executives, and the executive responds in the usual fashion by issuing a series of commands to the appropriate people lower in the hierarchy, who in turn do the same. Each of the executives and workers of the company knows how to complete many different tasks and executes them in the light of current conditions when instructed to do so. Good companies have mechanisms for ensuring that the programs of action at different levels of the hierarchy are well coordinated and effective. In the sensorimotor system, these mechanisms seem to be the responsibility of the cerebellum and basal ganglia.

Characteristics of Central Sensorimotor Programs

LO 8.22 Describe the various characteristics of central sensorimotor programs.

CENTRAL SENSORIMOTOR PROGRAMS ARE CAPABLE OF MOTOR EQUIVALENCE. Like a large, efficient company, the sensorimotor system does not always accomplish a particular task in exactly the same way. The fact that the same basic movement can be carried out in different ways involving different muscles is called **motor equivalence**. For example, you have learned to sign your name with stereotypical finger and hand movements, yet if you wrote your name with your toe on a sandy beach, your signature would still retain many of its typical characteristics.

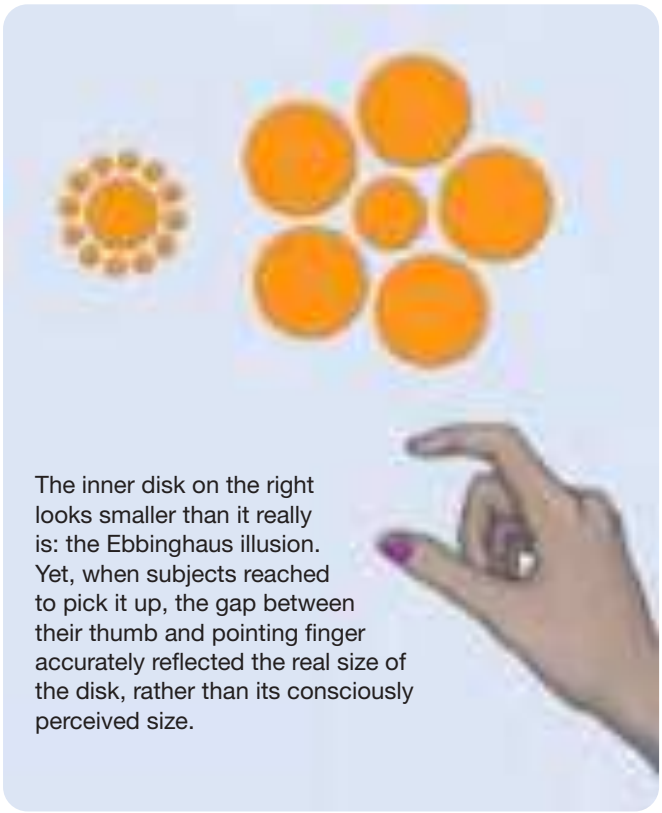
Motor equivalence illustrates the inherent plasticity of the sensorimotor system. It suggests that specific central sensorimotor programs for signing your name are not stored in the neural circuits that directly control your preferred hand; general programs are stored higher in your sensorimotor hierarchy and then are adapted to the situation as required. In an fMRI study, Rijntjes and others (1999) showed that the central sensorimotor programs for signing one's name seem to be stored in areas of secondary motor cortex that control the preferred hand. Remarkably, these same hand areas were also activated when the signature was made with a toe.

SENSORY INFORMATION THAT CONTROLS CENTRAL SENSORIMOTOR PROGRAMS IS NOT NECESSARILY CONSCIOUS. In Chapter 6, you learned that the neural mechanisms of conscious visual perception (ventral stream) are not necessarily the same as those that mediate the visual control of behavior (dorsal stream). Initial evidence for this theory came from neuropsychological patients who could respond to visual stimuli of which they had little conscious awareness and from others who could not effectively interact with objects that they consciously perceived.

Is there evidence for the separation of conscious perception and sensory control of behavior in intact humans? Haffenden and Goodale (1998) supplied such evidence (see also Ganel, Tanzer, & Goodale, 2008; Goodale & Westwood, 2004). They showed healthy volunteers a three-dimensional version of the visual illusion in Figure 8.15—notice that the two central disks appear to be different sizes, even though they are identical. Remarkably, when the volunteers were asked to indicate the size of each central disk with their right thumb and pointing finger, they judged the disk on the left to be bigger than the one on the right; however, when they were asked to reach out and pick up the disks with the same two digits, the preparatory gap between the digits was a function of the actual size of each disk rather than its perceived size.

CENTRAL SENSORIMOTOR PROGRAMS CAN DEVELOP WITHOUT PRACTICE. Although central sensorimotor programs for some behaviors can be established by practicing the behaviors, the central sensorimotor programs for many species-typical behaviors are established without explicit practice of the behaviors. This point was made clear by the classic study of Fentress (1973). Fentress showed that adult mice raised from birth without forelimbs still made the patterns of shoulder movements typical of grooming in their species—and that these movements were well coordinated with normal tongue, head, and eye movements. For example, the mice blinked each time they made the shoulder movements that would have swept their forepaws across their eyes. Fentress's study also demonstrated the importance of sensory feedback in the operation of central sensorimotor programs. The forelimbless mice, deprived of normal tongue–forepaw contact during face grooming, would often interrupt ostensible grooming sequences to lick a cage-mate or even the floor.

Figure 8.15 The Ebbinghaus illusion. Notice that the central disk on the left appears larger than the one on the right. In fact, both central disks are exactly the same size. Haffenden and Goodale (1998) found that when volunteers reached out to pick up either of the central disks, the position of their fingers as they approached the disks indicated that their responses were being controlled by the actual sizes of the disks, not their consciously perceived sizes.



The inner disk on the right looks smaller than it really is: the Ebbinghaus illusion. Yet, when subjects reached to pick it up, the gap between their thumb and pointing finger accurately reflected the real size of the disk, rather than its consciously perceived size.

PRACTICE CAN CREATE CENTRAL SENSORIMOTOR PROGRAMS. Although central sensorimotor programs for many species-typical behaviors develop without practice, practice can generate or modify them. Theories of sensorimotor learning emphasize two kinds of processes that influence the learning of central sensorimotor programs: response chunking and shifting control to lower levels of the sensorimotor system.

Response Chunking According to the **response-chunking hypothesis**, practice combines the central sensorimotor programs that control individual responses into programs that control sequences (chunks) of behavior. In a novice typist, each response necessary to type a word is individually triggered and controlled; in a skilled typist, sequences of letters are activated as a unit, with a marked increase in speed and continuity.

An important principle of chunking is that chunks can themselves be combined into higher-order chunks. For example, the responses needed to type the individual letters and digits of one's address may be chunked into longer sequences necessary to produce the individual words and numbers, and these chunks may in turn be combined so that the entire address can be typed as a unit.

Shifting Control to Lower Levels In the process of learning a central sensorimotor program, control is shifted from higher levels of the sensorimotor hierarchy to lower levels (see Bassett et al., 2015; Kawai et al., 2015; Makino et al., 2016). Shifting the level of control to lower levels of the sensorimotor system during training has two advantages. One is that it frees up the higher levels of the system to deal with more esoteric aspects of performance. For example, skilled pianists can concentrate on interpreting a piece of music because they do not have to consciously focus on pressing the right keys. The other advantage of shifting the level of control is that it permits great speed because different circuits at the lower levels of the hierarchy can act simultaneously,

without interfering with one another. It is possible to type 120 words per minute only because the circuits responsible for activating each individual key press can become active before the preceding response has been completed.

Functional Brain Imaging of Sensorimotor Learning

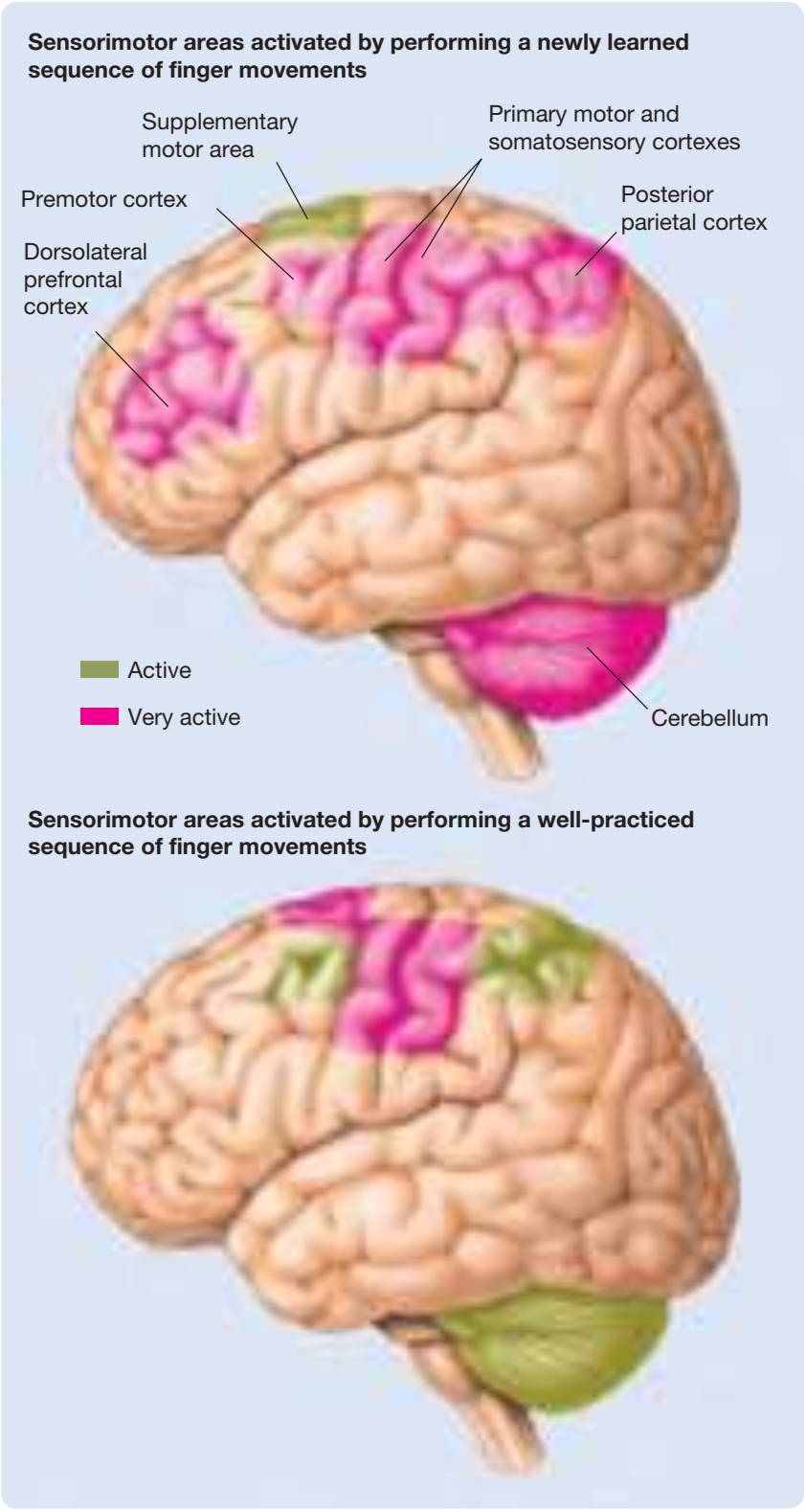
LO 8.23 **Explain how the classic Jenkins and colleagues PET study of simple motor learning summarizes the main points of this chapter.**

Functional brain-imaging techniques have provided opportunities for studying gross neural correlates of sensorimotor learning. By recording the brain activity of human volunteers as they learn to perform new motor sequences, researchers can develop hypotheses about the roles of various structures in sensorimotor learning. One of the first studies of this type was the PET study of Jenkins and colleagues (1994). These researchers recorded PET activity from human volunteers who performed two different sequences of key presses. There were four different keys, and each sequence was four presses long. The presses were performed with the right hand, one every 3 seconds, and tones indicated when to press and whether or not a press was correct. There were three conditions: (1) a rest control condition, (2) a condition in which the volunteers performed a newly learned sequence, and (3) a condition in which they performed a well-practiced sequence.

The results of Jenkins and colleagues are summarized in Figure 8.16. Notice two things. First, notice the involvement of the cortical sensorimotor areas that you were introduced to in this chapter. Second, notice how the involvement of association areas and the cerebellum diminished when sequences were well practiced.

The Jenkins and colleagues brain-imaging study of sensorimotor learning and subsequent studies like it (e.g., Bassett et al., 2015; Ostry & Gribble, 2015) have made important contributions by identifying where changes occur in the brain while volunteers learn sensorimotor tasks. But what is the nature of those changes? The next section addresses this question.

Figure 8.16 The activity recorded by PET scans during the performance of newly learned and well-practiced sequences of finger movements.



Based on Jenkins, I. H., Brooks, D. J., Bixon, P. D., Frackowiak, R. S. J., & Passingham, R. E. (1994). Motor sequence learning: A study with positron emission tomography. *Journal of Neuroscience*, *14*(6), 3775–3790.

Neuroplasticity Associated with Sensorimotor Learning

LO 8.24 Describe two examples of neuroplasticity—one at the cortical level and one at the subcortical level.

The learning of new sensorimotor tasks is accompanied by both cortical and subcortical changes. First, at the level of the motor cortex, there is a strengthening of the inputs from the thalamus and from other areas of motor cortex with learning. Such strengthening is related to an increase in the number of dendritic spines—which suggests an increase in the number of synapses (see Peters et al., 2017).

Second, there is a large increase in the number of oligodendrocytes (glia that produce myelin sheaths in the CNS; see Chapter 4) in subcortical white matter just after sensorimotor learning. This increase in the number of oligodendrocytes is presumably due to an increased demand for myelination of new and/or existing axonal connections (see Xiao et al., 2016).

The Case of Rhonelle, Revisited

A few days after we finished writing this chapter, I (JP) stopped off to pick up a few fresh vegetables and some fish for dinner, and I once again found myself waiting in Rhonelle's line. It was the longest line, but I am a creature of habit. This time, I felt rather smug as I watched her. All of the reading and thinking that had gone into the preparation of this chapter had provided me with some new insights into what she was doing and how she was doing it. I wondered whether she appreciated her own finely tuned sensorimotor system as much as I did.

Then I hatched my plot—a little test of Rhonelle's muscle-spindle feedback system. How would Rhonelle's finely tuned sensorimotor system react to a bag that looked heavy but was in fact extremely light? Next time, I would get one of those paper bags at the mushroom counter, blow it up, drop one mushroom in it, and then fold the top so it looked completely full. I smiled at the thought. But I wasn't the only one smiling. My daydreaming ended abruptly, and the smile melted from my face as I noticed Rhonelle's amused grin. Will I never learn?

Themes Revisited

All four of this text's major themes were addressed in this chapter. Most prominent was the clinical implications theme. You learned how research with neuropsychological patients with sensorimotor deficits, as well as with normal human volunteers, has contributed to current theories of sensorimotor functioning.

The evolutionary perspective theme was evident in the discussion of several comparative experiments on the sensorimotor system, largely in nonhuman primates. An important point to keep in mind is that although the sensorimotor functions of nonhuman primates are similar to those of humans, they are not identical (e.g., monkeys walk on both hands and feet). Remarkably, programs for walking tend to be similar in humans, other mammals, and birds.

You learned how metaphors can be used to think productively about science—in particular, how a large, efficient company can serve as a useful metaphor for the sensorimotor system. You also learned how recent analyses have suggested that primary motor cortex encodes the end point of movements rather than the movements themselves.

You also learned that the sensorimotor system is fundamentally plastic. General commands to move are issued by cortical circuits, but exactly how a movement is actually completed depends on the current situation (e.g., body position). Moreover, the sensorimotor system maintains the ability to change itself in response to learning and practice.

Finally, one of the two emerging themes, consciousness, was present in the pervasive discussion of conscious versus unconscious control of movement, as can be demonstrated with the Ebbinghaus illusion.

Key Terms

Three Principles of Sensorimotor Function

Sensory feedback, p. 215

Sensorimotor Association Cortex

Posterior parietal association cortex, p. 216
Frontal eye field, p. 217
Apraxia, p. 217
Contralateral neglect, p. 217
Dorsolateral prefrontal association cortex, p. 218

Secondary Motor Cortex

Secondary motor cortex, p. 219
Supplementary motor area, p. 219
Premotor cortex, p. 219
Mirror neurons, p. 219

Primary Motor Cortex

Primary motor cortex, p. 221
Somatotopic, p. 221
Motor homunculus, p. 221
Stereognosis, p. 221

Epilogue

It is the summer of 2020, and it is a very different world from when we started writing this edition of *Biopsychology* almost two years ago. We are now living in the midst of the vast social and political changes brought on by the COVID-19 pandemic. We are also seeing great efforts to battle racism, and to address accessibility and equity issues faced by racialized persons and other marginalized groups in our society. The fact that such efforts are so prominent during a pandemic speaks to how pressing the need is to deal with these social injustices.

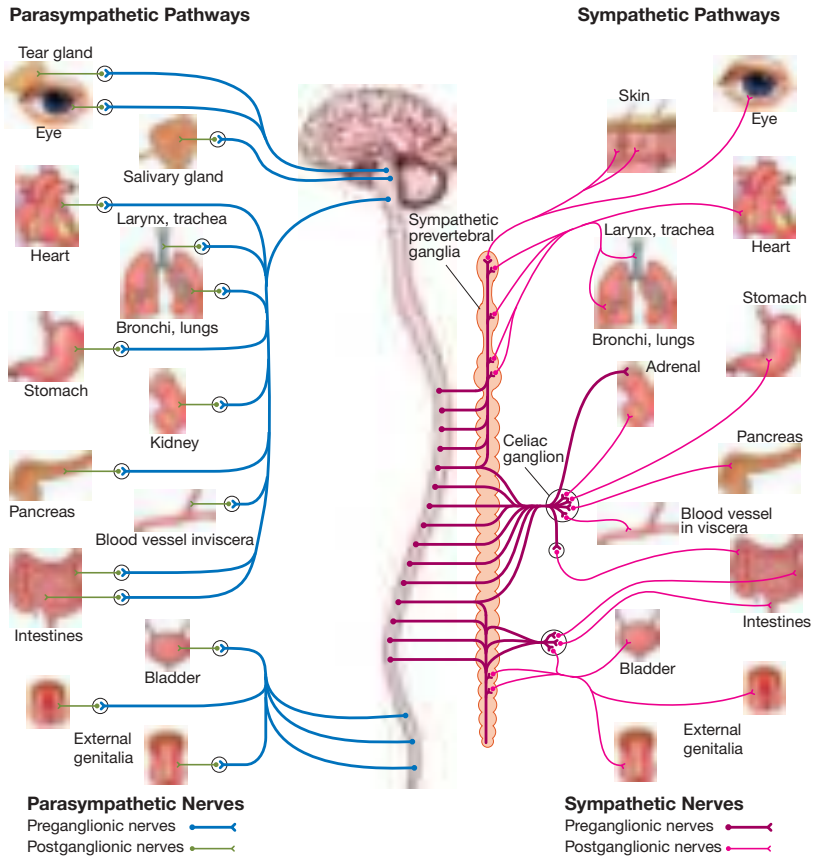
We feel relieved to be finishing *Biopsychology*, and we are excited by the prospect of being able to speak to so many students like you through this new edition. You must also feel relieved to be finishing this course; still, we hope that you feel a tiny bit of regret that our time together is over. Like good friends, we have shared good times and bad. We have shared the fun and wonder of Rhonelle, the dexterous cashier; the Nads basketball team; people who rarely sleep; the "mamawawa"; and split brains. But we have also been touched by many personal tragedies: for example, the victims of Alzheimer's disease and MPTP poisoning; Jimmie G.; H.M.; the man who mistook his wife for a hat; Professor P., the biopsychologist who experienced brain surgery from the other side of the knife; and S.B., the biopsychology student who guided the treatment of his own disease. Thank you for allowing us to share biopsychology with you. We hope you have found it to be an enriching experience.

As the founder and primary author of *Biopsychology* for eleven editions now, I (JP) am excited by the prospect that Steven Barnes will be carrying this book forward into future editions. Steven is a gifted writer, educator, researcher, and artist. His approach is eclectic. Although I will miss writing this book, I find comfort in the thought that I leave you in Steven's capable hands.

Right now, John Pinel is sitting in his home looking out over his garden and the Pacific Ocean, and Steven Barnes is sitting on the shores of a Rocky Mountain lake with his daughter. Our writing of this edition is complete. John's garden is calling for his attention, and the lake waters are calling for Steven to dive in. It is the afternoon of Friday, July 24, 2020.

Appendix I

The Autonomic Nervous System (ANS)



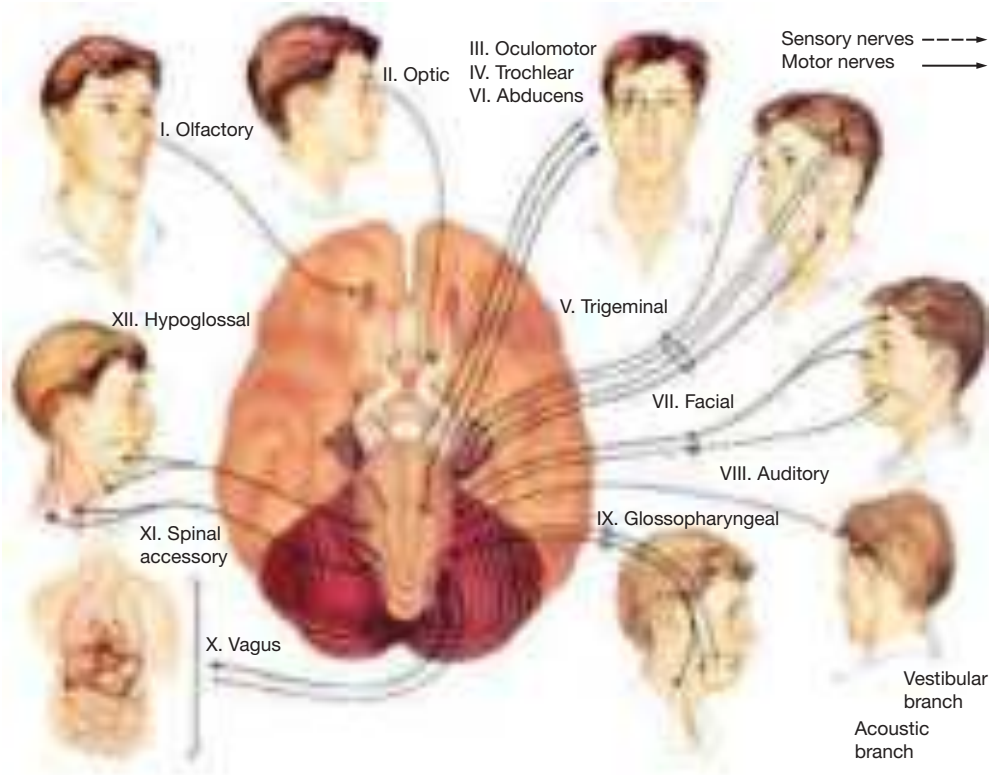
Appendix II

Some Functions of Sympathetic and Parasympathetic Neurons

Organ	Sympathetic Effect	Parasympathetic Effect
Salivary gland	Decreases secretion	Increases secretion
Heart	Increases heart rate	Decreases heart rate
Blood vessels	Constricts blood vessels in most organs	Dilates blood vessels in a few organs
Penis	Ejaculation	Erection
Iris radial muscles	Dilates pupils	No effect
Iris sphincter muscles	No effect	Constricts pupils
Tear gland	No effect	Stimulates secretion
Sweat gland	Stimulates secretion	No effect
Stomach and intestine	No effect	Stimulates secretion
Lungs	Dilates bronchioles; inhibits mucous secretion	Constricts bronchioles; stimulates mucous secretion
Arrector pili muscles	Erects hair and creates gooseflesh	No effect

Appendix III

The Cranial Nerves



Appendix IV

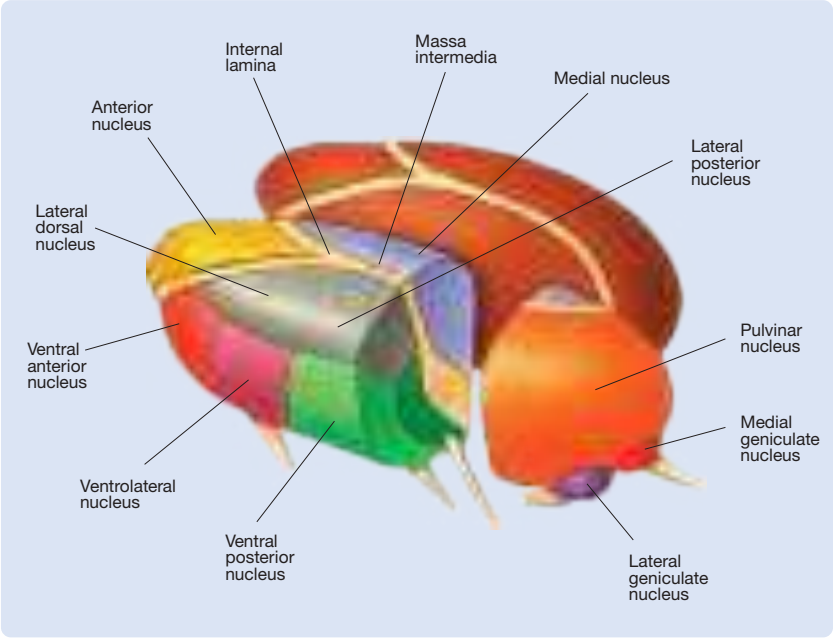
Functions of the Cranial Nerves

Number	Name	General Function	Specific Functions
I	Olfactory	Sensory	Smell
II	Optic	Sensory	Vision
III	Oculomotor	Motor	Eye movement and pupillary constriction
		Sensory	Sensory signals from certain eye muscles
IV	Trochlear	Motor	Eye movement
		Sensory	Sensory signals from certain eye muscles
V	Trigeminal	Sensory	Facial sensations
		Motor	Chewing
VI	Abducens	Motor	Eye movement
		Sensory	Sensory signals from certain eye muscles
VII	Facial	Sensory	Taste from anterior two-thirds of tongue
		Motor	Facial expression, secretion of tears, salivation, cranial blood vessel dilation
VIII	Auditory-Vestibular	Sensory	Audition; sensory signals from the organs of balance in the inner ear
IX	Glossopharyngeal	Sensory	Taste from posterior third of tongue
		Motor	Salivation, swallowing
X	Vagus	Sensory	Sensations from abdominal and thoracic organs
		Motor	Control over abdominal and thoracic organs and muscles of the throat
XI	Spinal Accessory	Motor	Movement of neck, shoulders, and head
		Sensory	Sensory signals from muscles of the neck
XII	Hypoglossal	Motor	Tongue movements
		Sensory	Sensory signals from tongue muscles

NOTE: Some authors describe cranial nerves III, IV, VI, XI, and XII as purely motor. However, each of these cranial nerves contains a small proportion of sensory fibers that conduct information from receptors to the brain. This sensory information is necessary for directing the respective cranial nerve's motor responses. See the discussion of sensory feedback in Chapter 8.

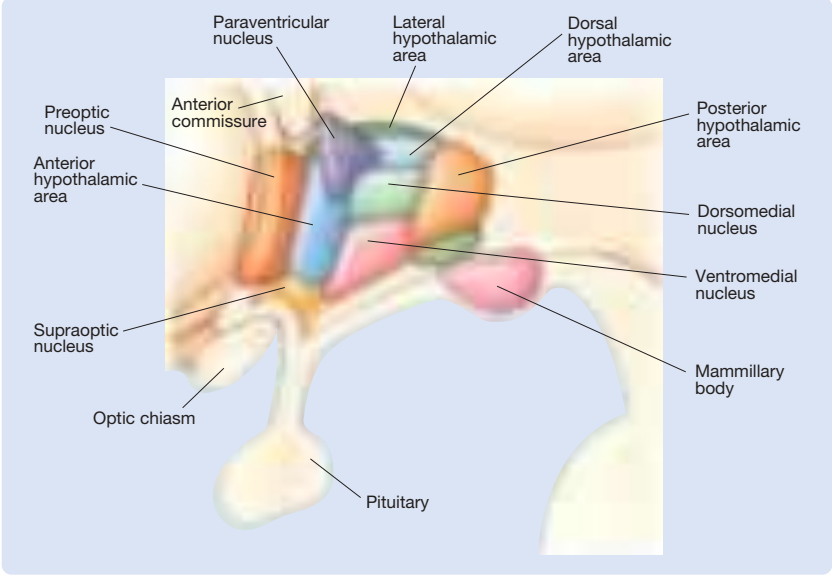
Appendix V

Nuclei of the Thalamus



Appendix VI

Nuclei of the Hypothalamus



Glossary

3-per-second spike-and-wave discharge. The characteristic EEG pattern of the absence seizure.

5-hydroxytryptophan (5-HTP). The precursor of serotonin.

Ablatio penis. Accidental destruction of the penis via surgery.

Absence seizure. A type of generalized seizure whose primary behavioral symptom is a disruption of consciousness associated with a cessation of ongoing behavior, a vacant look, and sometimes fluttering eyelids.

Absolute refractory period. A brief period (typically 1 to 2 milliseconds) after the initiation of an action potential during which it is impossible to elicit another action potential in the same neuron.

Absorption spectrum. A graph of the ability of a substance to absorb light of different wavelengths.

Absorptive phase. The metabolic phase during which the body is operating on the energy from a recently consumed meal and is storing the excess as body fat, glycogen, and proteins.

Accommodation. The process of adjusting the configuration of the lenses to bring images into focus on the retina.

Acetylcholine. A neurotransmitter that is created by the addition of an acetyl group to a choline molecule.

Acetylcholinesterase. The enzyme that breaks down the neurotransmitter acetylcholine.

Acquired dyslexias. Dyslexias caused by brain damage in people previously capable of reading.

Action potential (AP). A massive momentary reversal of a neuron's membrane potential from about –70 mV to about +50 mV.

Activation-synthesis hypothesis. The theory that the information supplied to the cortex by the brain stem during REM sleep is largely random and that the resulting dream is the cortex's best effort to make sense of those random signals.

Activators. Proteins that bind to DNA and increase gene expression.

Active placebos. Control drugs that have no therapeutic effect but produce side effects similar to those produced by the drug under evaluation in a clinical trial.

Acuity. The ability to see the details of objects.

Adaptation theories of sleep. Theories of sleep based on the premise that sleep evolved to protect organisms from predation and accidents and to conserve their energy rather than to fulfill some particular physiological need.

Adaptive immune system. The division of the immune system that mounts targeted attacks on foreign pathogens by binding to antigens in their cell membranes.

Adipsia. Complete cessation of drinking.

Adjustable gastric band procedure. A surgical procedure for treating obesity in which an adjustable band is implanted around the stomach to reduce the flow of food.

Adrenal cortex. The outer layer of each adrenal gland, which releases glucocorticoids in response to stressors, as well as small amounts of steroid hormones.

Adrenal medulla. The core of each adrenal gland, which releases epinephrine and norepinephrine in response to stressors.

Adrenalectomy. Surgical removal of the adrenal glands.

Adrenocorticotropic hormone (ACTH). An anterior pituitary hormone that triggers the release of adrenal hormones from the adrenal cortices.

Adrenogenital syndrome. Caused by congenital adrenal hyperplasia, which results in the excessive release of adrenal androgens which have masculinizing effects in females.

Afferent nerves. Nerves that carry sensory signals to the central nervous system.

Ageusia. The inability to taste.

Aggregation. The alignment of neurons during the development of the nervous system.

Aggressive behaviors. Behaviors whose primary function is to threaten or harm other organisms.

Agnosia. A failure of recognition of sensory stimuli that is not attributable to a sensory or to verbal or intellectual impairment.

Agonists. Drugs that facilitate the effects of a particular neurotransmitter.

Agoraphobia. Pathological fear of public places and open spaces.

Agraphia. A specific inability to write; one that does not result from general visual, motor, or intellectual deficits.

Akinetopsia. A deficiency in the ability to see movement progress in a smooth fashion, which often results from damage to the MT area.

Alexia. A specific inability to read; one that does not result from general visual, motor, or intellectual deficits.

Alleles. The two genes that control the same trait.

All-or-none responses. Responses that are not graded; they either occur to their full extent or do not occur at all.

Alpha fetoprotein. A protein that is present in the blood of many mammals during the perinatal period and that deactivates circulating estradiol by binding to it.

Alpha male. The dominant male of a colony.

Alpha waves. Regular, 8- to 12-per-second, high-amplitude EEG waves that typically occur during relaxed wakefulness and just before falling asleep.

Alzheimer's disease. The most common form of dementia in the elderly. Its three defining characteristics are: neurofibrillary tangles, amyloid plaques, and neuron loss.

Amacrine cells. Retinal neurons that are specialized for lateral communication.

Amino acid derivative hormones. Hormones that are synthesized in a few simple steps from an amino acid molecule.

Amino acid neurotransmitters. A class of small-molecule neurotransmitters, which includes the amino acids glutamate, aspartate, glycine, and GABA.

Amino acids. The building blocks of proteins.

Amnesia. Any pathological loss of memory.

Amphetamine. A stimulant drug.

Amphibians. Species that must live in water during their larval phase; adult amphibians can survive on land.

Amygdala. A structure in the anterior temporal lobe, just anterior to the hippocampus; plays a role in emotion.

Anabolic steroids. Steroid drugs that are similar to testosterone and have powerful anabolic (growth-promoting) effects.

Analgesics. Drugs that reduce pain.

Analogous. Having a similar structure because of convergent evolution (e.g., a bird's wing and a bee's wing are analogous).

Anandamide. The first endogenous endocannabinoid to be discovered and characterized.

Androgen insensitivity syndrome. Results from a mutation to the androgen receptor gene that renders the androgen receptors unresponsive and leads to the development of a female body.

Androgens. The class of steroid hormones that includes testosterone.

Androstenedione. The adrenal androgen that is responsible for the growth of pubic hair and axillary hair in human females.

Aneurysm. A pathological balloonlike dilation that forms in the wall of an artery at a point where the elasticity of the artery wall is defective.

Angular gyrus. The gyrus of the posterior cortex at the boundary between the temporal and parietal lobes. According to the Wernicke-Geschwind model the left hemisphere angular gyrus plays a role in reading.

Anhedonia. A general inability to experience pleasure.

Anorexia nervosa. An eating disorder of underconsumption that results in health-threatening weight loss.

Anosmia. The inability to smell.

Anosognosia. The common failure of neuropsychological patients to recognize their own symptoms.

Antagonistic muscles. Pairs of muscles that act in opposition.

Antagonists. Drugs that inhibit the effects of a particular neurotransmitter.

Anterior. Toward the nose end of a vertebrate.

Anterior cingulate cortex. The cortex of the anterior cingulate gyrus.

Anterior pituitary. The part of the pituitary gland that releases tropic hormones.

Anterograde amnesia. Loss of memory for events occurring after the amnesia-inducing brain injury.

Anterograde degeneration. The degeneration of the distal segment of a cut axon.

Anterolateral system. A major somatosensory pathway that ascends in the anterolateral portion of the spinal cord and tends to carry information related to pain and temperature.

Antibodies. Proteins that bind to foreign antigens on the surface of microorganisms and in so doing promote the destruction of the microorganisms.

Antibody-mediated immunity. The immune reaction in which B cells destroy invading microorganisms via the production of antibodies.

Antidromic conduction. Axonal conduction opposite to the normal direction; conduction from axon terminals back toward the cell body.

Antigens. Molecules, usually proteins, that can trigger an immune response.

Antihypnotic drugs. Sleep-reducing drugs.

Anxiety. Chronic fear that persists in the absence of any direct threat.

Anxiety disorder. A psychiatric disorder that involves anxiety that is so extreme and so pervasive that it disrupts normal functioning.

Anxiolytic drugs. Drugs that have antianxiety effects.

Anxiolytics. Antianxiety drugs.

Aphagia. Complete cessation of eating.

Aphasia. A brain damage–produced deficit in the ability to produce or comprehend language.

Apoptosis. Cell death that is actively induced by genetic programs; programmed cell death.

Appetizer effect. The increase in hunger that is produced by the consumption of small amounts of food.

Applied research. Research that is intended to bring about some direct benefit to humankind.

Apraxia. A disorder in which patients have great difficulty performing movements when asked to do so out of context but can readily perform them spontaneously in natural situations.

Arachnoid membrane. The meninx that is located between the dura mater and the pia mater and has the appearance of a gauzelike spiderweb.

Arcuate fasciculus. The major neural pathway between Broca's area and Wernicke's area.

Arcuate nucleus. A nucleus of the hypothalamus that contains high concentrations of both leptin receptors and insulin receptors.

Area MT. An area of cortex, located near the junction of the temporal, parietal, and occipital lobes, whose function appears to be the perception of motion.

Aromatase. An enzyme that promotes the conversion of testosterone to estradiol.

Aromatization. The chemical process by which testosterone is converted to estradiol.

Aromatization hypothesis. The hypothesis that the brain is masculinized by estradiol that is produced from perinatal testosterone through a process called *aromatization*.

Arteriosclerosis. A condition in which blood vessels are narrowed or blocked by the accumulation of fat deposits on their walls.

Asomatognosia. A deficiency in the awareness of parts of one's own body that is typically produced by damage to the right parietal lobe.

Aspartate. An amino acid neurotransmitter.

Aspiration. A lesion technique in which tissue is drawn off by suction through the fine tip of a glass pipette.

Association cortex. An area of cortex that receives input from more than one sensory system.

Astereognosia. An inability to recognize objects by touch that is not attributable to a simple sensory deficit or to an intellectual impairment.

Astrocytes. Large, star-shaped glial cells that play multiple roles in the central nervous system.

Ataxia. A loss of motor coordination.

Atropine. A receptor blocker that exerts its antagonistic effect by binding to muscarinic receptors.

Attentional gaze. The shift in attention from one perceptual object to another.

Atypical antidepressants. A catch-all class for antidepressant drugs that do not fit into the other categories of antidepressants (e.g., monoamine oxidase inhibitors, tricyclic antidepressants). Each of the drugs in this class has its own unique mechanism of action.

Atypical antipsychotics. Drugs that are effective against schizophrenia but yet do not bind strongly to D_2 receptors. Also known as *second-generation antipsychotics*.

Auditory nerve. The branch of cranial nerve VIII that carries auditory signals from the hair cells in the basilar membrane.

Autism spectrum disorder (ASD). A complex neurodevelopmental disorder characterized by a reduced capacity for social interaction and communication and restricted and repetitive patterns of behavior, interests, or activities.

Autonomic nervous system (ANS). The part of the peripheral nervous system that participates in the regulation of the body's internal environment.

Autoradiography. The technique of photographically developing brain slices that have been exposed to a radioactively labeled substance (such as 2-deoxyglucose) so that regions of high uptake are made visible.

Autoreceptors. A type of metabotropic receptor located on the presynaptic membrane that bind to their neuron's own neurotransmitters.

Autosomal chromosomes. Chromosomes that come in matched pairs; in mammals, all of the chromosomes except the sex chromosomes are autosomal.

Axon hillock. The conical structure at the junction between the axon and cell body.

Axon initial segment. The segment of the axon where action potentials are generated—located immediately adjacent to the axon hillock.

B cells. B lymphocytes; lymphocytes that manufacture antibodies against antigens they encounter.

Basal forebrain. A midline area of the forebrain, which is located just in front of and above the hypothalamus and is the brain's main source of acetylcholine.

Basal ganglia. A collection of subcortical nuclei (e.g., striatum and globus pallidus).

Basal metabolic rate. The rate at which energy is utilized to maintain bodily processes when resting.

Basilar membrane. The membrane of the organ of Corti in which the hair cell receptors are embedded.

Before-and-after design. The experimental design used to demonstrate contingent drug tolerance; one group receives the drug before each of a series of behavioral tests and the other group receives the drug after each test.

Behavioral paradigm. A single set of procedures developed for the investigation of a particular behavioral phenomenon.

Benign tumors. Tumors that are surgically removable with little risk of further growth in the body.

Benzodiazepines. A class of $GABA_A$ agonists with anxiolytic, sedative, and anticonvulsant properties; drugs such as chlordiazepoxide (Librium) and diazepam (Valium).

Beta-amyloid. A protein that is present in normal brains in small amounts. Beta amyloid is a major constituent of the amyloid plaques of Alzheimer's disease.

Between-subjects design. An experimental design in which a different group of subjects is tested under each condition.

Bilateral medial temporal lobectomy. The removal of the medial portions of both temporal lobes, including the hippocampus, the amygdala, and the adjacent cortex.

Binding problem. When the brain combines individual sensory attributes to produce integrated perceptions.

Binocular. Cells in the visual system that are binocular respond to stimulation of either eye.

Binocular disparity. The difference in the position of the same image on the two retinas.

Biopsychology. The scientific study of the biology of behavior; a biological approach to the study of psychology.

Bipolar cells. Bipolar neurons that form the middle layer of the retina.

Bipolar disorders. A category of psychiatric disorders that involves alternate bouts of depression and mania or hypomania.

Bipolar disorder type I. A psychiatric disorder that involves alternate bouts of depression and mania.

Bipolar disorder type II. A psychiatric disorder that involves alternate bouts of depression and hypomania.

Bipolar neuron. A neuron with two processes extending from its cell body.

Bisexual. An individual who is sexually attracted to members of both sexes.

Bistable figures. A stimulus that produces two alternating perceptions.

Blind spot. The area on the retina where the bundle of axons from the retinal ganglion cells leave the eye as the optic nerve.

Blindsight. The ability to respond to visual stimuli in a scotoma without conscious awareness of those stimuli.

Blood–brain barrier. The mechanism that impedes the passage of toxic substances from the blood into the brain.

BOLD signal. The blood-oxygen-level-dependent signal that is recorded by functional MRI (fMRI).

Botox. *Botulinium toxin*; a neurotoxin released by bacterium often found in spoiled food. It blocks the release of acetylcholine at neuromuscular junctions and has applications in medicine and cosmetics.

Bottom-up. A sort of neural mechanism that involves activation of higher cortical areas by lower cortical areas.

Brain-derived neurotrophic factor. One type of neurotrophin.

Brain stem. The part of the brain on which the cerebral hemispheres rest; in general, it regulates reflex activities that are critical for survival (e.g., heart rate and respiration).

Bregma. The point on the surface of the skull where two of the major sutures intersect; commonly used as a reference point in stereotaxic surgery on rodents.

Broca's aphasia. A hypothetical disorder of speech production with no associated deficits in language comprehension.

Broca's area. The area of the inferior prefrontal cortex of the left hemisphere hypothesized by Broca to be the center of speech production.

Buerger's disease. A condition in which the blood vessels, especially those supplying the legs, are constricted whenever tobacco is smoked. The disease can progress to gangrene and amputation.

Bulimia nervosa. An eating disorder characterized by periods of not eating interrupted by bingeing followed by purging.

Bullying. A chronic social threat that induces subordination stress in members of our species.

Butyrophenones. A class of antipsychotic drugs that bind primarily to D_2 receptors.

CA1 subfield. A region of the hippocampus that is commonly damaged by cerebral ischemia.

Cafeteria diet. A diet offered to experimental animals that is composed of a wide variety of palatable foods.

***Cannabis*.** The common hemp plant, which is the source of marijuana.

Cannon-Bard theory. The theory that emotional experience and emotional expression are parallel processes that have no direct causal relation.

Cannula. A fine, hollow tube that is implanted in the body for the purpose of introducing or extracting substances.

Carbon monoxide. A soluble-gas neurotransmitter.

Carousel apparatus. An apparatus used to study the effects of sleep deprivation in laboratory rats.

Cartesian dualism. The philosophical position of René Descartes, who argued that the universe is composed of two elements: physical matter and the human mind.

Case studies. Studies that focus on a single case, or subject.

Cataplexy. A disorder that is characterized by recurring losses of muscle tone during wakefulness and is often seen in cases of narcolepsy.

Catecholamines. The three monoamine neurotransmitters that are synthesized from the amino acid tyrosine: dopamine, epinephrine, and norepinephrine.

Caudate. The tail-like structure that is part of the striatum.

Cell-adhesion molecules (CAMs). Molecules on the surface of cells that have the ability to recognize specific molecules on the surface of other cells and adhere to them.

Cell-mediated immunity. The immune reaction by which T cells destroy invading microorganisms.

Central canal. The small cerebrospinal fluid-filled channel that runs the length of the spinal cord.

Central fissure. The large fissure that separates the frontal lobe from the parietal lobe.

Central nervous system (CNS). The portion of the nervous system within the skull and spine.

Central nucleus of the amygdala. A nucleus of the amygdala that is thought to control defensive behavior.

Central sensorimotor programs. Patterns of activity that are programmed into the sensorimotor system.

Cephalic phase. The metabolic phase during which the body prepares for food that is about to be absorbed.

Cerebellum. A metencephalic structure that is thought to participate in the storage of memories of learned sensorimotor skills.

Cerebral angiography. A contrast x-ray technique for visualizing the cerebral circulatory system by infusing a radio-opaque dye into a cerebral artery.

Cerebral aqueduct. A narrow channel that connects the third and fourth ventricles.

Cerebral commissures. Tracts that connect the left and right cerebral hemispheres.

Cerebral cortex. The layer of neural tissue covering the cerebral hemispheres of humans and other mammals.

Cerebral dialysis. A method for recording changes in brain chemistry in behaving animals in which a fine tube with a short semipermeable section is implanted in the brain and extracellular neurochemicals are continuously drawn off for analysis.

Cerebral hemorrhage. Bleeding in the brain.

Cerebral ischemia. An interruption of the blood supply to an area of the brain.

Cerebral ventricles. The four cerebrospinal fluid-filled internal chambers of the brain: the two lateral ventricles, the third ventricle, and the fourth ventricle.

Cerebrospinal fluid (CSF). The fluid that fills the subarachnoid space, the central canal, and the cerebral ventricles.

Cerebrum. The portion of the brain that sits above the brain stem; in general, it plays a role in complex adaptive processes (e.g., learning, perception, and motivation).

Cerveau isolé preparation. An experimental preparation in which the forebrain is disconnected from the rest of the brain by a midcollicular transection.

Change blindness. The difficulty perceiving major changes to unattended-to parts of a visual image when the changes are introduced during brief interruptions in the presentation of the image.

Charles Bonnet syndrome. A condition, most commonly seen in people with glaucoma, wherein affected individuals experience rich and complex hallucinations (e.g., people's faces, complex landscapes).

Cheese effect. The surges in blood pressure that occur when individuals taking MAO inhibitors consume tyramine-rich foods, such as cheese.

Chemoaffinity hypothesis. The hypothesis that growing axons are attracted to the correct targets by different chemicals released by the target sites.

Chemotopic. Organized, like the olfactory bulb, according to a map of various odors.

Chimeric figures test. A test of visual completion in split-brain subjects that uses pictures composed of the left and right halves of two different faces.

Chlorpromazine. The first antipsychotic drug.

Cholecystokinin (CCK). A peptide that is released by the gastrointestinal tract and is thought to function as a satiety signal.

Chordates. Animals with dorsal nerve cords.

Choroid plexuses. The networks of capillaries that protrude into the ventricles from the pia mater and produce cerebrospinal fluid.

Chromosomes. Threadlike structures in the cell nucleus that contain the genes; each chromosome is a DNA molecule.

Chronic traumatic encephalopathy. The dementia and cerebral scarring observed in boxers, rugby players, American football players, and other individuals who have experienced repeated concussive, or even subconcussive, blows to the head.

Chronobiotic. A substance that influences the timing of internal biological rhythms.

Ciliary muscles. The eye muscles that control the shape of the lenses.

Cingulate cortex. The cortex of the cingulate gyri, which are located on the medial surfaces of the frontal lobes.

Cingulate gyri. Large gyri located on the medial surfaces of the frontal lobes, just superior to the corpus callosum.

Cingulate motor areas. Two small areas of secondary motor cortex located in the cortex of the cingulate gyrus of each hemisphere.

Circadian clock. An internal timing mechanism that is capable of maintaining daily cycles of physiological functions.

Circadian rhythms. Daily cycles of bodily functions.

Cirrhosis. Scarring of the liver, which is a major cause of death among heavy alcohol users.

Clinical. Pertaining to illness or treatment.

Clinical depression (major depressive disorder). Depression that is so severe that it is difficult for the patient to meet the essential requirements of daily life.

Clinical trials. Studies conducted on human subjects to assess the therapeutic efficacy of an untested drug or other treatment.

Closed-head tramautic brain injuries (TBIs). Brain injuries produced by blows that do not penetrate the skull.

Clozapine. An atypical antipsychotic that is used to treat schizophrenia, does not produce Parkinsonian side effects, and has only a slight affinity for D_2 receptors.

Cocaine. A stimulant that exerts its effects by altering the activity of dopamine transporters.

Cocaine psychosis. Psychotic symptoms that are sometimes observed during cocaine sprees; similar in certain respects to schizophrenia.

Cocaine sprees. Binges of cocaine use.

Cochlea. The long, coiled tube in the inner ear that is filled with fluid and contains the organ of Corti and its auditory receptors.

Cocktail-party phenomenon. The ability to unconsciously monitor the contents of one conversation while consciously focusing on another.

Cocontraction. The simultaneous contraction of antagonistic muscles.

Codeine. A relatively weak psychoactive ingredient of opium.

Codon. A group of three consecutive nucleotide bases on a DNA or messenger RNA strand; each codon specifies the particular amino acid that is to be added to an amino acid chain during protein synthesis.

Coexistence. The presence of more than one neurotransmitter in the same neuron.

Cognition. Higher intellectual processes such as thought, memory, attention, and complex perceptual processes.

Cognitive neuroscience. A division of biopsychology that focuses on the use of functional brain imaging to study the neural mechanisms of human cognition.

Collateral sprouting. The growth of axon branches from mature neurons, usually to postsynaptic sites abandoned by adjacent axons that have degenerated.

Colony-intruder paradigm. A paradigm for the study of aggressive and defensive behaviors in male rats; a small male intruder rat is placed in an established colony in order to study the aggressive responses of the colony's alpha male and the defensive responses of the intruder.

Color constancy. The tendency of an object to appear the same color even when the wavelengths of light that it reflects change.

Columnar organization. The functional organization of the neocortex in vertical columns; the cells in each column form a mini-circuit that performs a single function.

Commissurotomy. Surgical severing of the cerebral commissures.

Comorbid. The tendency for two or more health conditions to occur together in the same individual.

Comparative approach. The study of biological processes by comparing different species—usually from the evolutionary perspective.

Comparative psychology. The division of biopsychology that studies the evolution, genetics, and adaptiveness of behavior, often by using the comparative approach.

Complementary colors. Pairs of colors that produce white or gray when combined in equal measure.

Completion. The visual system's automatic use of information obtained from receptors around the blind spot, or scotoma, to create a perception of the missing portion of the retinal image.

Complex cells. Neurons in the visual cortex that respond optimally to straight-edge stimuli in a certain orientation in any part of their receptive field.

Complex seizures. Seizures that are characterized by various complex psychological phenomena and are thought to originate in the temporal lobes.

Component theory. The theory that the relative amount of activity produced in three different classes of cones by light determines its perceived color (also called *trichromatic theory*).

Computed tomography (CT). A computer-assisted x-ray procedure that can be used to visualize the brain and other internal structures of the living body.

Concept cells. Cells, such as those found in the medial temporal lobe, that respond to ideas or concepts rather than to particulars. Also known as *Jennifer Aniston neurons*.

Conditioned compensatory responses. Hypothetical conditional physiological responses that are opposite to the effects of a drug that are thought to be elicited by stimuli that are regularly associated with experiencing the drug effects.

Conditioned defensive burying. The burial of a source of aversive stimulation by rats.

Conditioned drug tolerance. Tolerance effects that are maximally expressed only when a drug is administered in the same situation in which it has previously been administered.

Conditioned place-preference paradigm. A test that assesses a laboratory animal's preference for an environment in which it has previously experienced drug effects relative to a control environment.

Conditioned taste aversion. An avoidance response that develops to the taste of food whose consumption has been followed by illness.

Conduction aphasia. A hypothetical aphasia that is thought to result from damage to the arcuate fasciculus—the pathway between Broca's and Wernicke's areas.

Cones. The visual receptors in the retina that mediate high acuity color vision in good lighting.

Confounded variable. An unintended difference between the conditions of an experiment that could have affected the dependent variable.

Congenital. Present at birth.

Congenital adrenal hyperplasia. A congenital deficiency in the release of cortisol from the adrenal cortex, which leads to the excessive release of adrenal androgens.

Conscious awareness. The awareness of one's perceptions; typically inferred from the ability to verbally describe them.

Consciousness. The perception or awareness of some aspect of one's self or the world.

Conspecifics. Members of the same species.

Constituent cognitive processes. Simple cognitive processes that combine to produce complex cognitive processes.

Contextual fear conditioning. The process by which benign contexts (situations) come to elicit fear through their association with fear-inducing stimuli.

Contingent drug tolerance. Drug tolerance that develops as a reaction to the experience of the effects of drugs rather than to drug exposure alone.

Contralateral. Projecting from one side of the body to the other.

Contralateral neglect. A disturbance of the patient's ability to respond to stimuli on the side of the body opposite to a site of brain damage, usually the left side of the body following damage to the right parietal lobe.

Contrast enhancement. The intensification of the perception of edges.

Contrast x-ray techniques. X-ray techniques that involve the injection, into one compartment of the body, of a substance that absorbs x-rays either less than or more than surrounding tissues.

Contrecoup injuries. Contusions that occur on the side of the brain opposite to the side of a blow.

"Control of behavior" versus "conscious perception" theory. The theory that the dorsal stream mediates behavioral interactions with objects and the ventral stream mediates conscious perception of objects.

Control-question technique. A lie-detection interrogation method in which the polygrapher compares the physiological responses to target questions with the responses to control questions.

Contusions. Closed-head injuries that involve damage to the cerebral circulatory system, which produces internal hemorrhaging.

Convergent evolution. The evolution in unrelated species of similar solutions to the same environmental demands.

Converging operations. The use of several research approaches to solve a single problem.

Convolutions. Folds on the surface of the cerebral hemispheres.

Convulsions. Motor seizures.

Coolidge effect. The fact that a copulating male who becomes incapable of continuing to copulate with one sex partner can often recommence copulating with a new sex partner.

Copulation. Sexual intercourse.

Corpus callosum. The largest cerebral commissure.

Corticosterone. The predominant glucocorticoid in humans.

Crack. A potent, cheap, smokable form of cocaine.

Cranial nerves. The 12 pairs of nerves extending from the brain (e.g., optic nerves, olfactory nerves, and vagus nerves).

Critical period. A period during development in which a particular experience must occur for it to influence the course of subsequent development.

Critical thinking. The process of recognizing the weaknesses of existing ideas and the evidence on which they are based.

Cross-cuing. Communication between hemispheres that have been separated by commissurotomy via an external route.

Cross section. Section cut at a right angle to any long, narrow structure of the central nervous system.

Cross tolerance. Tolerance to the effects of one drug that develops as the result of exposure to another drug that acts by the same mechanism.

CRISPR/Cas9 method. A popular gene editing technique. It allows researchers to edit parts of the genome by removing from, adding to, or altering the DNA sequence.

Cytokines. A group of peptide hormones that are released by many cells and participate in a variety of physiological and immunological responses, causing inflammation and fever.

Decorticate. Lacking a cortex.

Decussate. To cross over to the other side of the brain.

Deep brain stimulation. A treatment in which low intensity electrical stimulation is continually applied to an area of the brain through an implanted electrode.

Deep dyslexia. A reading disorder in which the phonetic procedure is disrupted while the lexical procedure is not.

Default mode. The pattern of brain activity that is present when humans sit quietly and let their minds wander.

Default mode network. The network of brain structures that tends to be active when the brain is in default mode.

Defeminizes. Suppresses or disrupts female characteristics.

Defensive behaviors. Behaviors whose primary function is protection from threat or harm.

Defensive-burying test. An animal model of anxiety; anxious rats will bury objects that generate anxiety.

Delayed nonmatching-to-sample test. A test in which the subject is presented with an unfamiliar sample object and then, after a delay, is presented with a choice between the sample object and an unfamiliar object, where the correct choice is the unfamiliar object.

Delirium tremens (DTs). The phase of alcohol withdrawal syndrome characterized by hallucinations, delusions, disorientation, agitation, confusion, hyperthermia, and tachycardia.

Delta waves. The largest and slowest EEG waves.

Demasculinizes. Suppresses or disrupts male characteristics.

Dementia. General intellectual deterioration.

Dendritic spines. Tiny protrusions of various shapes that are located on the surfaces of many dendrites.

Deoxyribonucleic acid (DNA). The double-stranded, coiled molecule of genetic material.

Dependent variable. The variable measured by the experimenter to assess the effect of the independent variable.

Depolarize. To decrease the resting membrane potential.

Depressant. A drug that depresses neural activity.

Desynchronized EEG. Low-amplitude, high-frequency EEG.

Developmental dyslexias. Dyslexias that become apparent when a child is learning to read.

Dextrals. Right-handers.

Dichotic listening test. A test of language lateralization in which two different sequences of three spoken digits are presented simultaneously, one to each ear, and the subject is asked to report all of the digits heard.

Dichotomous traits. Traits that occur in one form or the other, never in combination.

Diencephalon. One of the five major divisions of the brain; it is composed of the thalamus and hypothalamus.

Diet-induced thermogenesis. The homeostasis-defending increases in body temperature that are associated with increases in body fat.

Diffusion tensor MRI. A magnetic resonance imaging (MRI) technique that is used for identifying major tracts.

Digestion. The process by which food is broken down and absorbed through the lining of the gastrointestinal tract.

Digit span. The longest sequence of random digits that can be repeated correctly 50 percent of the time—most people have a digit span of 7.

Directed synapses. Synapses at which the site of neurotransmitter release and the site of neurotransmitter reception are in close proximity.

Distal. Far from something.

Distal segment. The segment of a cut axon between the cut and the axon terminals.

Dizygotic twins. Twins that develop from two zygotes and thus tend to be as genetically similar as any pair of siblings.

DNA methylation. An epigenetic mechanism wherein a methyl group attaches to a DNA molecule, usually at cytosine sites in mammals. DNA methylation can either decrease or increase gene expression.

Dominant hemisphere. A term used in the past to refer to the left hemisphere, based on the incorrect assumption that the left hemisphere is dominant in all complex behavioral and cognitive activities.

Dominant trait. The trait of a dichotomous pair that is expressed in the phenotypes of heterozygous individuals.

Dopamine. One of the three catecholamine neurotransmitters.

Dopamine transporters. Molecules in the presynaptic membrane of dopaminergic neurons that attract dopamine molecules in the synaptic cleft and deposit them back inside the neuron.

Dorsal. Toward the surface of the back of a vertebrate or toward the top of the head.

Dorsal-column medial-lemniscus system. The division of the somatosensory system that ascends in the dorsal portion of the spinal white matter and tends to carry signals related to touch and proprioception.

Dorsal columns. The somatosensory tracts that ascend in the dorsal portion of the spinal cord white matter.

Dorsal horns. The two dorsal arms of the spinal gray matter.

Dorsal root ganglia. Structures just outside the spinal cord that are composed of the cell bodies of dorsal root axons.

Dorsal stream. The group of visual pathways that flows from the primary visual cortex to the dorsal prestriate cortex to the posterior parietal cortex.

Dorsolateral prefrontal association cortex. An area of the prefrontal cortex that plays a role in the evaluation of external stimuli and the initiation of complex voluntary motor responses.

Down syndrome. A disorder associated with the presence of an extra chromosome 21, resulting in disfigurement and intellectual impairment.

Drug-addicted individuals. Those habitual drug users who continue to use a drug despite its adverse effects on their health and social life and despite their repeated efforts to stop using it.

Drug craving. An affective state in which there is a strong desire for a particular drug.

Drug metabolism. The conversion of a drug from its active form to a nonactive form.

Drug priming. A single exposure to a formerly abused drug.

Drug self-administration paradigm. A test of the addictive potential of drugs in which laboratory animals can inject drugs into themselves by pressing a lever.

Drug sensitization. An increase in the sensitivity to a drug effect that develops as the result of exposure to the drug.

Drug tolerance. A state of decreased sensitivity to a drug that develops as a result of exposure to the drug.

DSM-5. The fifth and current edition of the *Diagnostic and Statistical Manual of Mental Disorders;* produced by the American Psychiatric Association.

Dual-trace theory. The theory that memories are temporarily stored in the hippocampus until they can be transferred to a more stable cortical storage system. Also known as the *standard consolidation theory*.

Duchenne smile. A genuine smile, one that includes contraction of the facial muscles called the *orbicularis oculi*.

Duodenum. The upper portion of the intestine through which most of the glucose and amino acids are absorbed into the bloodstream.

Duplexity theory. The theory that cones and rods mediate photopic and scotopic vision, respectively.

Dura mater. The tough outer meninx.

Dynamic contraction. Contraction of a muscle that causes the muscle to shorten.

Dynamic phase. The first phase of the VMH syndrome, characterized by grossly excessive eating and rapid weight gain.

Dyslexia. A reading disorder that does not result from general visual, motor, or intellectual deficits.

Efferent nerves. Nerves that carry motor signals from the central nervous system to the skeletal muscles or internal organs.

Ejaculate. To eject sperm from the penis.

Ejaculation. Ejection of sperm.

Electrocardiogram (ECG or EKG). A recording of the electrical signals associated with heartbeats.

Electroconvulsive shock (ECS). An intense, brief, diffuse, seizure-inducing current administered to the brain via large electrodes attached to the scalp.

Electroencephalogram (EEG). A measure of the gross electrical activity of the brain, commonly recorded through scalp electrodes.

Electroencephalography. A technique for recording the gross electrical activity of the brain through electrodes, which in humans are usually attached to the surface of the scalp.

Electromyogram (EMG). A record of muscle tension.

Electromyography. A procedure for measuring muscle tension.

Electron microscopy. A microscopy technique used to study the fine details of cellular structure.

Electrooculogram (EOG). A measure of eye movement.

Electrooculography. A technique for recording eye movements through electrodes placed around the eye.

Elevated plus maze. An apparatus for recording defensiveness or anxiety in rats by assessing their tendency to avoid the two open arms of a plus sign–shaped maze mounted some distance above the floor.

Elevated-plus-maze test. An animal model of anxiety; anxious rats tend to stay in the enclosed arms of the maze rather than venturing onto the open arms.

Embolism. The blockage of blood flow in a smaller blood vessel by a plug that was formed in a larger blood vessel and carried by the bloodstream to the smaller one.

Emergent stage 1 EEG. All periods of stage 1 sleep EEG except initial stage 1; each is associated with REMs.

Empathogens. Psychoactive drugs that produce feelings of empathy.

Encapsulated tumors. Tumors that grow within their own membrane.

Encéphale isolé preparation. An experimental preparation in which the brain is separated from the rest of the nervous system by a transection of the caudal brain stem.

Encephalitis. The inflammation associated with brain infection.

Endocannabinoids. A class of unconventional neurotransmitters that are chemically similar to the active components of marijuana.

Endocrine glands. Ductless glands that release chemicals called *hormones* directly into the circulatory system.

Endogenous. Naturally occurring in the body (e.g., endogenous opioids).

Endogenous depression. Depression that occurs with no apparent cause.

Endorphins. A class of endogenous opioids.

Engram. A change in the brain that stores a memory.

Engram cells. Neurons that maintain an engram.

Enhancers. Stretches of DNA that control the rate of expression of target genes.

Enkephalins. The first class of endogenous opioids to be discovered.

Enriched environments. Laboratory environments designed to promote cognitive and physical activity by providing opportunities for a greater variety of sensory and motor experiences than available in conventional laboratory environments; commonly used to study the effects of experience on development in rats and mice.

Entorhinal cortex. An area of the medial temporal cortex that is a major source of neural signals to the hippocampus.

Enzymatic degradation. The breakdown of chemicals by enzymes—one of the two mechanisms for deactivating released neurotransmitters.

Enzymes. Proteins that stimulate or inhibit biochemical reactions without being affected by them.

Epidemiology. The study of the factors that influence the distribution of a disease in the general population.

Epigenetics. The study of all mechanisms of inheritance other than the genetic code and its expression.

Epigenetic. Not of the genes; refers to nongenetic means by which traits are passed from parents to offspring.

Epigenome. A catalogue of all the epigenetic mechanisms at play within a particular cell type.

Epilepsy. A neurological disorder characterized by spontaneously recurring seizures.

Epileptic auras. Psychological changes that precede the onset of a seizure.

Epileptogenesis. Development of epilepsy.

Epinephrine. One of the three catecholamine neurotransmitters.

Episodic memories. Explicit memories for the particular events and experiences of one's life.

Epitranscriptome. Refers to all those modifications of RNA that occur after transcription—that do not involve modifications to the RNA base sequence.

Estradiol. The most common estrogen.

Estrogens. The class of steroid hormones that are released in large amounts by the ovaries; an example is estradiol.

Estrous cycle. The cycle of sexual receptivity displayed by many female mammals.

Estrus. The portion of the estrous cycle characterized by proceptivity, sexual receptivity, and fertility (*estrus* is a noun and *estrous* an adjective).

Ethological research. The study of animal behavior in its natural environment.

Ethology. The study of the behavior of animals in their natural environments.

Euthymic. Individuals who are not currently displaying symptoms of depression, hypomania, or mania.

Event-related potentials (ERPs). The EEG waves that regularly accompany certain psychological events.

Evolutionary perspective. The approach that focuses on the environmental pressures that likely led to the evolution of the characteristics (e.g., of brain and behavior) of current species.

Evolve. To undergo gradual orderly change.

Exaptation. A characteristic that evolved to serve one function and was later co-opted to serve another function.

Excitatory postsynaptic potentials (EPSPs). Graded postsynaptic depolarizations, which increase the likelihood that an action potential will be generated.

Executive function. A collection of cognitive abilities (e.g., innovative thinking, lateral thinking, and insightful thinking) that appear to depend on the prefrontal cortex.

Exocrine glands. Glands that release chemicals into ducts that carry them to targets, mostly on the surface of the body.

Exocytosis. The process of releasing a neurotransmitter.

Explicit memories. Conscious memories.

Expressive. Pertaining to the generation of language; that is, pertaining to writing or talking.

Extensors. Muscles that act to straighten or extend a joint.

Exteroceptive stimuli. Stimuli that arise from outside the body.

Facial feedback hypothesis. The hypothesis that our facial expressions can influence the emotions we experience.

Far-field potentials. EEG signals recorded in attenuated form at the scalp because they originate far away—for example, in the brain stem.

Fasciculation. The tendency of developing axons to grow along the paths established by preceding axons.

Fasting phase. The metabolic phase that begins when energy from the preceding meal is no longer sufficient to meet the immediate needs of the body and during which energy is extracted from fat and glycogen stores.

Fear. The emotional reaction that is normally elicited by the presence or expectation of threatening stimuli.

Fear conditioning. Establishing fear of a previously neutral conditional stimulus by pairing it with an aversive unconditional stimulus.

Feminizes. Enhances or produces female characteristics.

Fetal alcohol syndrome (FAS). A syndrome produced by prenatal exposure to alcohol and characterized by brain damage, intellectual disability, poor coordination, poor muscle tone, low birth weight, retarded growth, and/or physical deformity.

Fissures. The large furrows in a convoluted cortex.

Fitness. According to Darwin, the ability of an organism to survive and contribute its genes to the next generation.

Fixational eye movements. Involuntary movements of the eyes (tremor, drifts, and saccades) that occur when a person tries to fix their gaze on (i.e., stare at) a point.

Flavor. The combined impression of taste and smell.

Flexors. Muscles that act to bend or flex a joint.

Fluorodeoxyglucose (FDG). A molecule that is similar to glucose, and is thus rapidly taken up by active cells. However, unlike glucose, fluorodeoxyglucose cannot be metabolized; it therefore accumulates in active cells until it is gradually broken down. A radioactive isotope of this molecule is commonly used in positron emission tomography (PET).

Fluoxetine. The first selective serotonin reuptake inhibitor (SSRI) to be developed. It was initially marketed under the trade-name *Prozac*.

Focal seizure. A seizure that does not involve the entire brain.

Follicle-stimulating hormone (FSH). The gonadotropic hormone that stimulates development of ovarian follicles.

Fornix. The major tract of the limbic system; it connects the hippocampus with the septum and mammillary bodies.

Fourier analysis. A mathematical procedure for breaking down a complex wave form into component sine waves of various frequencies.

Fovea. The central indentation of the retina, which is specialized for high-acuity vision.

Fraternal birth order effect. The finding that the probability of a male being attracted to other males increases as a function of the number of older brothers he has.

Free fatty acids. The main source of the body's energy during the fasting phase; released from adipose tissue in response to high levels of glucagon.

Free nerve endings. Neuron endings that lack specialized structures on them and that detect cutaneous pain and changes in temperature.

Free-running period. The duration of one cycle of a free-running rhythm.

Free-running rhythms. Circadian rhythms that do not depend on environmental cues to keep them on a regular schedule.

Frontal eye field. A small area of prefrontal cortex that controls eye movements.

Frontal lobe. The most anterior of the four cerebral lobes.

Frontal operculum. The area of prefrontal cortex that in the left hemisphere is the location of Broca's area.

Frontal sections. Any slices of brain tissue cut in a plane that is parallel to the face; also termed *coronal sections*.

Functional connectivity. An approach used by cognitive neuroscientists that examines which brain regions have parallel activation patterns over time.

Functional connectome. A catalogue of the functional connectivity associated with each behavior and cognitive process.

Functional MRI (fMRI). A magnetic resonance imaging technique for inferring brain activity by measuring increased oxygen flow into particular areas.

Functional segregation. Organization into different areas, each of which performs a different function; for example, in sensory systems, different areas of secondary and association cortex analyze different aspects of the same sensory stimulus.

Functional tolerance. Drug tolerance that results from changes that reduce the reactivity of the sites of action to the drug.

Functional ultrasound imaging. A technique that uses ultrasound (sound waves of a higher frequency than we can hear) to measure changes in blood volume in particular brain regions.

Fusiform face area. An area of human cortex, located at the boundary between the occipital and temporal lobes, that is selectively activated by human faces.

G proteins. Proteins that are located inside neurons (and some other cells) and are attached to metabotropic receptors in the cell membrane.

Gametes. Egg cells and sperm cells.

Gamma-aminobutyric acid (GABA). The amino acid neurotransmitter that is synthesized from glutamate; the most prevalent inhibitory neurotransmitter in the mammalian central nervous system.

Ganglia. Clusters of neuronal cell bodies in the peripheral nervous system (singular *ganglion*).

Gap junctions. Narrow spaces between adjacent neurons that are bridged by fine tubular channels containing cytoplasm, through which electrical signals and small molecules can pass readily.

Gastric bypass. A surgical procedure for treating obesity in which the intestine is cut and connected to the upper portion of the stomach, which is isolated from the rest of the stomach by a row of staples.

Gastric ulcers. Painful lesions to the lining of the stomach or duodenum.

Gay. Sexually attracted to members of the same sex.

Gender dysphoria. The distress that can occur in people whose gender identity differs from their sex assigned at birth or sex-related physical characteristics.

Gender identity. The gender that a person most identifies with: female, male, some combination of male and female, neither female or male, or some other gender category.

Gene. A unit of inheritance; for example, the section of a chromosome that controls the synthesis of one protein.

Gene editing techniques. Techniques that allow researchers to edit genes at a particular time during development.

Gene expression. The production of the protein specified by a particular gene.

Gene knockin techniques. Procedures for creating organisms that have one or more additional genes.

Gene knockout techniques. Procedures for creating organisms that lack a particular gene.

General paresis. The mental illness and dementia resulting from a syphilitic infection.

Generalizability. The degree to which the results of a study can be applied to other individuals or situations.

Generalized anxiety disorder. An anxiety disorder characterized by stress responses and extreme feelings of anxiety and worry about a large number of different activities or events.

Generalized seizures. Seizures that involve the entire brain.

Genetic recombination. The meiotic process by which pairs of chromosomes cross over one another at random points, break apart, and exchange genes.

Genitals. The external reproductive organs.

Genotype. The traits that an organism can pass on to its offspring through its genetic material.

Glial cells. Several classes of nonneural cells of the nervous system.

Glia-mediated migration. One of two major modes of neural migration during development, by which immature neurons move away from the central canal along radial glial cells.

Gliomas. Brain tumors that develop from glial cells.

Global amnesia. Amnesia for information presented in all sensory modalities.

Global aphasia. Severe disruption of all language-related abilities.

Global cerebral ischemia. An interruption of blood supply to the entire brain.

Globus pallidus. A structure of the basal ganglia that is located between the putamen and thalamus.

Glucagon. A pancreatic hormone that promotes the release of free fatty acids from adipose tissue, their conversion to ketones, and the use of both as sources of energy.

Glucocorticoids. Steroid hormones that are released from the adrenal cortex in response to stressors.

Gluconeogenesis. The process by which protein is converted to glucose.

Glucose. A simple sugar that is the breakdown product of complex carbohydrates; it is the body's primary, directly utilizable source of energy.

Glucostatic theory. The theory that eating is controlled by deviations from a hypothetical blood glucose set point.

Glutamate. The most prevalent excitatory neurotransmitter in the central nervous system.

Glycine. An amino acid neurotransmitter.

Golgi complex. Structures in the cell bodies and terminal buttons of neurons that package neurotransmitters and other molecules in vesicles.

Golgi stain. A neural stain that completely darkens a few of the neurons in each slice of tissue, thereby revealing their silhouettes.

Golgi tendon organs. Receptors that are embedded in tendons and are sensitive to the amount of tension in the skeletal muscles to which their tendons are attached.

Gonadectomy. The surgical removal of the gonads (testes or ovaries); castration.

Gonadotropin. The pituitary tropic hormone that stimulates the release of hormones from the gonads.

Gonadotropin-releasing hormone. The hypothalamic releasing hormone that controls the release of the two gonadotropic hormones from the anterior pituitary.

Gonads. The testes and the ovaries.

Graded potentials. All postsynaptic potentials (i.e., both excitatory postsynaptic potentials and inhibitory postsynaptic potentials), are graded potentials, which means that the amplitudes of postsynaptic potentials are proportional to the intensity of the signals that elicit them: Weak signals elicit small PSPs, and strong signals elicit large ones.

Graded responses. Responses whose magnitude is proportional to the magnitude of the stimuli that elicit them.

Grammatical analysis. Analysis of the structure of language.

Gray matter. Portions of the nervous system that are gray because they are composed largely of cell bodies and unmyelinated interneurons.

Green fluorescent protein (GFP). A protein that is found in certain species of jellyfish and that fluoresces when exposed to blue light.

Grid cells. Entorhinal neurons that each have an extensive array of evenly spaced place fields, producing a pattern reminiscent of graph paper.

Growth cone. Amoebalike structure at the tip of each growing axon or dendrite that guides growth to the appropriate target.

Growth hormone. The anterior pituitary hormone that acts directly on bone and muscle tissue to produce the pubertal growth spurt.

Guilty-knowledge technique. A lie-detection method in which the polygrapher records autonomic nervous system responses to a list of control and crime-related information known only to the guilty person and the examiner; also known as the *concealed information test*.

Gut microbiome. The bacteria and other organisms that live inside our gastrointestinal tract.

Gyri. The cortical ridges that are located between fissures or sulci.

Hair cells. The receptors of the auditory system.

Haloperidol. A butyrophenone used as an antipsychotic drug.

Harrison Narcotics Act. The act passed in 1914 that made it illegal to sell or use opium, morphine, or cocaine in the United States.

Hashish. Dark corklike material extracted from the resin on the leaves and flowers of *Cannabis*.

Hedonic value. The amount of pleasure that is actually experienced as the result of some action.

Helping-hand phenomenon. The redirection of one hand of a split-brain patient by the other hand.

Hemianopsic. Having a scotoma that covers half of the visual field.

Hemispherectomy. The removal of one cerebral hemisphere.

Heritability estimate. A numerical estimate of the proportion of variability that occurred in a particular trait in a particular study and that resulted from the genetic variation among the subjects in that study.

Heroin. A semisynthetic opioid.

Heschl's gyrus. The temporal lobe gyrus that is the location of primary auditory cortex.

Heterosexual. Sexually attracted to members of the other sex.

Heterozygous. Possessing two different genes for a particular trait.

Hierarchical organization. Organization into a series of levels that can be ranked with respect to one another; for example, in sensory systems, primary cortex, secondary cortex, and association cortex perform progressively more detailed analyses.

Hippocampus. A structure of the medial temporal lobes that plays a role in various forms of memory.

Histone. A protein around which DNA is coiled.

Histone remodeling. An epigenetic mechanism wherein histones change their shape and in so doing influence the shape of the adjacent DNA. This can either increase or decrease gene expression.

Homeostasis. A stable internal environment.

Hominini. The tribe of primates that includes at least six genera: Australopithecus, Paranthropus, Sahelanthropus, Orrorin, Pan, and Homo.

Hominins. Primates of the same group that includes humans.

Homologous. Having a similar structure because of a common evolutionary origin (e.g., a human's arm and a bird's wing are homologous).

Homozygous. Possessing two identical genes for a particular trait.

Horizontal cells. Retinal neurons whose specialized function is lateral communication.

Horizontal sections. Any slices of brain tissue cut in a plane that are parallel to the top of the brain.

Hormones. Chemicals released by the endocrine system directly into the circulatory system.

Human Genome Project. The international research effort to construct a detailed map of the human chromosomes.

Human proteome. A map of the entire set of proteins encoded for by human genes.

Huntingtin. Dominant gene that is mutated in cases of Huntington's disease.

Huntingtin protein. Protein whose synthesis is controlled by the huntingtin gene and is thus abnormal in individuals with Huntington's disease.

Huntington's disease. A progressive terminal disorder of motor and intellectual function that is produced in adulthood by a dominant gene.

Hyperphagia. Excessive eating.

Hyperpolarize. To increase the resting membrane potential.

Hypersomnia. Disorders characterized by excessive sleep or sleepiness.

Hypertension. Chronically high blood pressure.

Hypnagogic hallucinations. Dreamlike experiences that occur during wakefulness.

Hypnotic drugs. Sleep-promoting drugs.

Hypomania. A state that is characterized by a reduced need for sleep, high energy, and positive affect. During periods of hypomania, people are talkative, energetic, impulsive, positive, and very confident.

Hypothalamic peptides. One of the five classes of neuropeptide transmitters; it consists of those first identified as hormones released by the hypothalamus.

Hypothalamopituitary portal system. The vascular network that carries hormones from the hypothalamus to the anterior pituitary.

Hypothalamus. The diencephalic structure that sits just below the anterior portion of the thalamus.

Hypoxia. Shortage of oxygen supply to tissue—for example, to the brain.

Iatrogenic. Physician-created.

Imidazopyridines. A class of $GABA_A$ agonists that were marketed for the treatment of insomnia.

Imipramine. The first tricyclic antidepressant drug.

Immune system. The system that protects the body against infectious microorganisms.

Immunization. The process of creating immunity through vaccination.

Immunocytochemistry. A procedure for locating particular proteins in the brain by labeling their antibodies with a dye or radioactive element and then exposing slices of brain tissue to the labeled antibodies.

Implicit memories. Memories that are expressed by improved performance without conscious recall or recognition.

Impotent. Unable to achieve a penile erection.

In situ hybridization. A technique for locating particular proteins in the brain; molecules that bind to the mRNA that directs the synthesis of the target protein are synthesized and labeled, and brain slices are exposed to them.

Incentive-sensitization theory. Theory that addictions develop when drug use sensitizes the neural circuits mediating wanting of the drug—not necessarily liking of the drug.

Incomplete-pictures test. A test of memory measuring the improved ability to identify fragmented figures that have been previously observed.

Incubation of drug craving. The time-dependent increase in cue-induced drug craving and relapse.

Independent variable. The difference between experimental conditions that is arranged by the experimenter.

Indolamines. The class of monoamine neurotransmitters that are synthesized from tryptophan; serotonin is the only member of this class found in the mammalian nervous system.

Infantile amnesia. The normal inability to recall events from early childhood.

Inferior. Toward the bottom of the primate head or brain.

Inferior colliculi. The structures of the tectum that receive auditory input from the superior olives.

Inferotemporal cortex. The cortex of the inferior temporal lobe, in which is located an area of secondary visual cortex.

Infiltrating tumors. Tumors that grow diffusely through surrounding tissue.

Inhibitory postsynaptic potentials (IPSPs). Graded postsynaptic hyperpolarizations, which decrease the likelihood that an action potential will be generated.

Initial stage 1 EEG. The period of the stage 1 EEG that occurs at the onset of sleep; it is not associated with REMs.

Innate immune system. The first component of the immune system to react. It reacts quickly and generally near points of entry of pathogens.

Insomnia. Sleeplessness.

Instinctive behaviors. Behaviors that occur in all like members of a species, even when there seems to have been no opportunity for them to have been learned.

Insulin. A pancreatic hormone that facilitates the entry of glucose into cells and the conversion of bloodborne fuels to forms that can be stored.

Integration. Adding or combining a number of individual signals into one overall signal.

Internal desynchronization. The cycling on different schedules of the free-running circadian rhythms of two or more different processes.

Interneurons. Neurons with short axons or no axons at all, whose function is to integrate neural activity within a single brain structure.

Interoceptive stimuli. Stimuli that arise from inside the body.

Intersexed person. A term used to refer to a person who is born with sexual anatomy that does not clearly fit into typical definitions of male and female sexual anatomy.

Intracranial self-stimulation (ICSS). The repeated performance of a response that delivers electrical stimulation to certain sites in the animal's brain.

Intrafusal motor neuron. A motor neuron that innervates an intrafusal muscle.

Intrafusal muscle. A threadlike muscle that adjusts the tension on a muscle spindle.

Intromission. Insertion of the penis into the vagina.

Ion channels. Pores in neural membranes through which specific ions pass.

Ionotropic receptors. Receptors that are associated with ligand-activated ion channels.

Ions. Positively or negatively charged particles.

Iproniazid. The first antidepressant drug; a monoamine oxidase inhibitor.

Ipsilateral. On the same side of the body.

Isometric contraction. Contraction of a muscle that increases the force of its pull but does not shorten the muscle.

James-Lange theory. The theory that emotion-inducing sensory stimuli are received and interpreted by the cortex, which triggers changes in the visceral organs via the autonomic nervous system and in the skeletal muscles via the somatic nervous system. Then, the autonomic and somatic responses trigger the experience of emotion in the brain.

Jet lag. The adverse effects on body function of the acceleration of zeitgebers during eastbound flights or their deceleration during westbound flights.

Ketamine. A drug that is a type of dissociative hallucinogen.

Ketones. Breakdown products of free fatty acids that are used by muscles as a source of energy during the fasting phase.

Kindling phenomenon. The progressive development and intensification of convulsions elicited by a series of periodic low-intensity brain stimulations—most commonly by daily electrical stimulations to the amygdala.

Kluver-Bucy syndrome. The syndrome of behavioral changes (e.g., lack of fear and hypersexuality) that is induced in primates by bilateral damage to the anterior temporal lobes.

Korsakoff's syndrome. A neuropsychological disorder that is common in alcoholics and whose primary symptoms include memory loss, sensory and motor dysfunction, and, in its advanced stages, severe dementia.

L-Dopa. The chemical precursor of dopamine, which is used in the treatment of Parkinson's disease.

Lateral. Away from the midline of the body of a vertebrate, toward the body's lateral surfaces.

Lateral fissure. The large fissure that separates the temporal lobe from the frontal lobe.

Lateral geniculate nuclei. The six-layered thalamic structures that receive input from the retinas and transmit their output to the primary visual cortex.

Lateral hypothalamus (LH). The area of the hypothalamus once thought to be the feeding center.

Lateral nucleus of the amygdala. The nucleus of the amygdala that plays the major role in the acquisition, storage, and expression of conditioned fear.

Lateralization of function. The unequal representation of various psychological functions in the two hemispheres of the brain.

Leaky-barrel model. An analogy for the settling-point model of body-fat regulation.

Learning. The brain's ability to change in response to experience.

Leptin. A protein normally synthesized in fat cells; it is thought to act as a negative feedback signal normally released by fat stores to decrease appetite and increase fat metabolism.

Lesbian. Women who are attracted to women.

Leucotome. A surgical device used in psychosurgery to cut out a core of brain tissue.

Leukocytes. White blood cells.

Lewy bodies. Clumps of proteins that can be found in the surviving dopaminergic neurons of the substantia nigra of Parkinson's patients.

Lexical procedure. A procedure for reading aloud that is based on specific stored information acquired about written words.

Ligand. A molecule that binds to another molecule; neurotransmitters are ligands of their receptors.

Limbic system. A collection of interconnected nuclei and tracts that ring the thalamus.

Lipids. Fats.

Lipogenesis. The production of body fat.

Lipolysis. The breakdown of body fat.

Lipostatic theory. The theory that eating is controlled by deviations from a hypothetical body-fat set point.

Lithium. A metallic ion that is a mood stabilizer; used in the treatment of bipolar disorders.

Lobectomy. An operation in which a lobe, or a major part of one, is removed from the brain.

Lobotomy. An operation in which a lobe, or a major part of one, is separated from the rest of the brain by a large cut but is not removed.

Longitudinal fissure. The large fissure that separates the two cerebral hemispheres.

Long-term depression (LTD). A long-lasting decrease in synaptic efficacy (the flip side of LTP) that occurs in response to prolonged low-frequency stimulation of presynaptic neurons.

Long-term memory. Memory for experiences that endures after the experiences are no longer the focus of attention.

Long-term potentiation (LTP). The enduring facilitation of synaptic transmission that occurs following activation of synapses by high-intensity, high-frequency stimulation of presynaptic neurons.

Lordosis. The arched-back, rump-up, tail-to-the-side posture of female rodent sexual receptivity.

Lordosis quotient. The proportion of mounts that elicit lordosis.

Luteinizing hormone (LH). The gonadotropic hormone that causes the developing ovum to be released from its follicle.

Lymphocytes. Specialized leukocytes that are produced in bone marrow and the thymus gland and play important roles in the body's immune reactions.

Lysergic acid diethylamide (LSD). Hallucinogenic drug that alters perception, emotion, and cognition.

Magnetic resonance imaging (MRI). A structural brain imaging procedure in which high-resolution images are constructed from the measurement of waves that hydrogen atoms emit when they are activated by radio-frequency waves in a magnetic field.

Magnetoencephalography (MEG). A technique for measuring changes in magnetic fields on the surface of the scalp that are produced by changes in underlying patterns of neural activity.

Magnocellular layers. The layers of the lateral geniculate nuclei that are composed of neurons with large cell bodies; the bottom two layers (also called *M layers*).

Malignant tumors. Tumors that are difficult to remove or destroy, and continue to grow after attempts to remove or destroy them.

Mammals. A class of animals whose young are fed from mammary glands.

Mammillary bodies. The pair of spherical nuclei that are located on the inferior surface of the hypothalamus.

Mania. A state that has the same features as hypomania but taken to an extreme; it also has additional symptoms, such as delusions of grandeur, overconfidence, and distractibility. Mania usually involves psychosis.

MAO inhibitors. Antidepressant drugs that increase the level of monoamine neurotransmitters by inhibiting the action of the enzyme monoamine oxidase.

Masculinizes. Enhances or produces male characteristics.

Massa intermedia. The neural structure located in the third ventricle that connects the two lobes of the thalamus.

Maternal immune hypothesis. The hypothesis that mothers become progressively more immune to some masculinizing hormone in their male fetuses; proposed to explain the fraternal birth order effect.

Mean difference image. In the context of functional neuroimaging, the average of the difference images (obtained via paired-image subtraction) obtained from multiple participants.

Medial. Toward the midline of the body.

Medial diencephalic amnesia. Amnesia that is associated with damage to the medial diencephalon (e.g., Korsakoff's amnesia).

Medial dorsal nuclei. The thalamic relay nuclei of the olfactory system.

Medial geniculate nuclei. The auditory thalamic nuclei that receive input from the inferior colliculi and project to primary auditory cortex.

Medial lemniscus. The somatosensory pathway between the dorsal column nuclei and the ventral posterior nucleus of the thalamus.

Medial preoptic area. The area of the hypothalamus that includes the sexually dimorphic nuclei and that plays a key role in the control of male sexual behavior.

Medial temporal cortex. Cortex in the medial temporal lobe that lies adjacent to the hippocampus and amygdala.

Medial temporal lobe amnesia. Amnesia associated with bilateral damage to the medial temporal lobes; its major features are anterograde and retrograde amnesia for explicit memories, with preserved intellectual functioning.

Mediodorsal nuclei. A pair of thalamic nuclei, damage to which is thought to be responsible for many of the memory deficits associated with Korsakoff's syndrome.

Meiosis. The process of cell division that produces cells (e.g., egg cells and sperm cells) with half the chromosomes of the parent cell.

Melanocortin system. Neurons in the arcuate nucleus that release melanocortins.

Melanocortins. A class of peptides that includes the gut satiety peptide α-melanocyte-stimulating hormone.

Melanopsin. Photopigment found in certain retinal ganglion cells that responds to changes in background illumination and plays a role in the entrainment of circadian rhythms.

Melatonin. A hormone that is synthesized from serotonin in the pineal gland, and is both a soporific and a chronobiotic.

Membrane potential. The difference in electrical charge between the inside and the outside of a cell.

Memory. The brain's ability to store and access the learned effects of experiences.

Memory consolidation. The transfer of short-term memories to long-term storage.

Meninges. The three protective membranes that cover the brain and spinal cord (singular *meninx*).

Meningiomas. Tumors that grow between the meninges.

Meningitis. Inflammation of the meninges, usually caused by bacterial infection.

Menstrual cycle. The hormone-regulated cycle in females of follicle growth, egg release, buildup of the uterus lining, and menstruation.

Mesencephalon. One of the five major divisions of the brain; it is composed of the tectum and tegmentum.

Mesocorticolimbic pathway. The component of the mesotelencephalic dopamine system that has cell bodies in the ventral tegmental area that project to various cortical and limbic sites.

Mesoderm layer. The middle of the three cell layers in the developing embryo.

Mesotelencephalic dopamine system. The ascending projections of dopamine-releasing neurons from the substantia nigra and ventral tegmental area of the mesencephalon into various regions of the telencephalon.

Messenger RNA. A strand of RNA that is transcribed from DNA and then moves out of the cell nucleus where it is translated into a protein.

Metabolic tolerance. Tolerance that results from a reduction in the amount of a drug getting to its sites of action.

Metabotropic receptors. Receptors that are associated with signal proteins and G proteins.

Metaplasticity. The modulation of long term potentiation (LTP) and/or long-term depression (LTD) induction by prior synaptic activity.

Metastatic tumors. Tumors that originate in one organ and spread to another.

Metencephalon. One of the five major divisions of the brain; it includes the pons and cerebellum.

Microelectrodes. Extremely fine recording electrodes, which are used for intracellular recording.

Microglia. Glial cells that respond to injury or disease by engulfing cellular debris and triggering inflammatory responses.

Microsleeps. Brief periods of sleep that occur in sleep-deprived subjects while they remain sitting or standing.

Migration. The movement of cells from their site of creation in the ventricular zone of the neural tube to their appropriate target location.

Mild TBI. When there is a disturbance of consciousness following a blow to the head and there is no evidence of contusion or other structural damage.

Minor hemisphere. A term used in the past to refer to the right hemisphere, based on the incorrect assumption that the left hemisphere is dominant.

Mirror neurons. Neurons that fire when an individual performs a particular goal-directed hand movement or when they observe the same goal-directed movement performed by another.

Mirror-like system. Areas of the cortex that are active both when a person performs a particular response and when the person perceives somebody else performing the same response.

Miscellaneous peptides. One of the five categories of neuropeptide transmitters; it include those neuropeptide transmitters that don't fit into one of the other four categories.

Mitosis. The process of cell division that produces cells with the same number of chromosomes as the parent cell.

Mixed state. A state that can occur in bipolar disorder type I, where the patient simultaneously displays symptoms of both depression and mania.

Monoamine neurotransmitters. Small-molecule neurotransmitters that are synthesized from monoamines and comprise two classes: catecholamines and indolamines.

Monocular. Involving only one eye.

Monogamy. A pattern of mate bonding in which one male and one female form an enduring bond.

Monophasic sleep cycles. Sleep cycles that regularly involve only one period of sleep per day, typically at night.

Monozygotic twins. Twins that develop from the same zygote and are thus genetically identical.

Mood stabilizers. Drugs that effectively treat depression or mania without increasing the risk of mania or depression, respectively.

Morgan's Canon. The rule that the simplest possible interpretation for a behavioral observation should be given precedence.

Morphine. The major psychoactive ingredient in opium.

Morris water maze. A pool of milky water that has a goal platform invisible just beneath its surface and is used to study the ability of rats to learn spatial locations.

Morris water maze test. A widely used test of spatial memory in which rats must learn to swim directly to a platform hidden just beneath the surface of a circular pool of murky water.

Motor end-plate. The receptive area on a muscle fiber at a neuromuscular junction.

Motor equivalence. The ability of the sensorimotor system to carry out the same basic movement in different ways that involve different muscles.

Motor homunculus. The somatotopic map of the human primary motor cortex.

Motor pool. All of the motor neurons that innervate the fibers of a given muscle.

Motor theory of speech perception. The theory that the perception of speech involves activation of the same areas of the brain that are involved in the production of speech.

Motor units. A single motor neuron and all of the skeletal muscle fibers that are innervated by it.

Movement vigor. The control of the speed and amplitude of movement based on motivational factors.

MPTP. A neurotoxin that produces a disorder in primates that is similar to Parkinson's disease.

Müllerian-inhibiting substance. The testicular hormone that causes the precursor of the female reproductive ducts (the Müllerian system) to degenerate and the testes to descend.

Müllerian system. The embryonic precursor of the female reproductive ducts.

Multiple sclerosis (MS). A progressive disease that attacks the myelin of axons in the central nervous system.

Multipolar neuron. A neuron with more than two processes extending from its cell body.

Multipotent. Capable of developing into different cells of only one class of cells (e.g., different kinds of blood cells).

Mumby box. An apparatus that is used in the rat version of the delayed nonmatching-to-sample test.

Muscle spindles. Receptors that are embedded in skeletal muscle tissue and are sensitive to changes in muscle length.

Mutations. Accidental alterations in individual genes.

Myelencephalon. The most posterior of the five major divisions of the brain; the medulla.

Myelin. A fatty insulating substance.

Myelin sheaths. Coverings on the axons of some neurons that are rich in myelin and increase the speed and efficiency of axonal conduction.

Narcolepsy. A disorder of hypersomnia that is characterized by repeated, brief daytime sleep attacks and cataplexy.

Narcotic. A legal term generally used to refer to opioids.

Nasal hemiretina. The half of each retina next to the nose.

Natural selection. The idea that those heritable traits that are associated with high rates of survival and reproduction are the most likely to be passed on to future generations.

Nature–nurture issue. The debate about the relative contributions of nature (genes) and nurture (experience) to the behavioral capacities of individuals.

NEAT. Nonexercise activity thermogenesis, which is generated by activities such as fidgeting and the maintenance of posture and muscle tone.

Necrosis. Passive cell death.

Negative feedback systems. Systems in which feedback from changes in one direction elicit compensatory effects in the opposite direction.

Negative symptoms. Symptoms of schizophrenia that seem to represent a reduction or loss of typical function.

Neocortex. Six-layered cerebral cortex of relatively recent evolution; it constitutes 90 percent of human cerebral cortex.

Neoplasm. Tumor; literally, "new growth."

Nerve growth factor (NGF). The first neurotrophin to be discovered.

Nerves. Bundles of axons in the peripheral nervous system.

Neural crest. A structure situated just dorsal to the neural tube. It is formed from cells that break off from the neural tube as it is being formed.

Neural plate. A small patch of ectodermal tissue on the dorsal surface of the vertebrate embryo, from which the neural groove, the neural tube, and, ultimately, the mature nervous system develop.

Neural proliferation. The rapid increase in the number of neurons that follows the formation of the neural tube.

Neural regeneration. The regrowth of damaged neurons.

Neural tube. The tube that is formed in the vertebrate embryo when the edges of the neural groove fuse and that develops into the central nervous system.

Neuroanatomy. The study of the structure of the nervous system.

Neurochemistry. The study of the chemical bases of neural activity.

Neuroendocrinology. The study of the interactions between the nervous system and the endocrine system.

Neurogenesis. The growth of new neurons.

Neuromuscular junctions. The synapses of a motor neuron on a muscle.

Neurons. Cells of the nervous system that are specialized for the reception, conduction, and transmission of electrochemical signals.

Neuropathic pain. Severe chronic pain in the absence of a recognizable pain stimulus.

Neuropathology. The study of nervous system disorders.

Neuropeptide. Short amino acid chains.

Neuropeptide transmitters. Peptides that function as neurotransmitters, of which about 100 have been identified; also called *neuropeptides*.

Neuropeptide Y. A gut hunger peptide.

Neuropharmacology. The study of the effects of drugs on neural activity.

Neurophysiology. The study of the functions and activities of the nervous system.

Neuroplasticity. The notion that the brain is a "plastic" (changeable) organ that continuously grows and changes in response to an individual's environment and experiences.

Neuropsychology. The division of biopsychology that studies the psychological effects of brain damage in human patients.

Neuroscience. The scientific study of the nervous system.

Neurotoxins. Neural poisons.

Neurotrophins. Chemicals that are supplied to developing neurons by their targets and that promote their survival.

Nicotine. The major psychoactive ingredient of tobacco.

Nigrostriatal pathway. The pathway along which axons from neurons in the substantia nigra project to the striatum.

Nissl stain. A neural stain that has an affinity for structures in neuron cell bodies.

Nitric oxide. A soluble-gas neurotransmitter.

NMDA (N-methyl-d-aspartate) receptors. Glutamate receptors that play key roles in the development of stroke-induced brain damage and long-term potentiation at glutaminergic synapses.

Nodes of Ranvier. The gaps between adjacent myelin sheaths on an axon.

Nondirected synapses. Synapses at which the site of neurotransmitter release and the site of neurotransmitter reception are not close together.

Nootropics (smart drugs). Drugs that purportedly improve memory.

Norepinephrine. One of the three catecholamine neurotransmitters.

Nuclei. The DNA-containing structures of cells; also, clusters of neuronal cell bodies in the central nervous system (singular *nucleus*).

Nucleotide bases. A class of chemical substances that includes adenine, thymine, guanine, and cytosine—constituents of DNA.

Nucleus accumbens. Nucleus of the ventral striatum and a major terminal of the mesocorticolimbic dopamine pathway.

Nucleus magnocellularis. The nucleus of the caudal reticular formation that promotes relaxation of the core muscles during REM sleep and during attacks of cataplexy.

Nutritive density. Calories per unit volume of a food.

Ob/ob mice. Mice that are homozygous for the mutant ob gene; their body fat produces no leptin, and they become very obese.

Occipital face area. An area in the occipital lobe that is implicated in the processing of faces.

Occipital lobe. The most posterior of the four cerebral lobes; its function is primarily visual.

Off-center cells. Visual neurons that respond to lights shone in the center of their receptive fields with "off" firing and to lights shone in the periphery of their receptive fields with "on" firing.

Olfactory bulbs. Their output goes primarily to the amygdala and piriform cortex.

Olfactory glomeruli. Discrete clusters of neurons that lie near the surface of the olfactory bulbs.

Olfactory mucosa. The mucous membrane that lines the upper nasal passages and contains the olfactory receptor cells.

Oligodendrocytes. Glial cells that myelinate axons of the central nervous system; also known as *oligodendroglia*.

Oligodendroglia. Glial cells that myelinate central nervous system axons; also known as *oligodendrocytes*.

On-center cells. Visual neurons that respond to lights shone in the center of their receptive fields with "on" firing and to lights shone in the periphery of their receptive fields with "off" firing.

Ontogeny. The development of individuals over their life span.

Open-field test. In this test an animal is placed in a large, barren chamber and its activity is recorded.

Operant conditioning paradigm. A paradigm in which the rate of a particular voluntary response is increased by reinforcement or decreased by punishment.

Opioids. Morphine, codeine, heroin, and other chemicals with similar structures or effects.

Opioid peptides. One of the five classes of neuropeptide transmitters; it consists of those with a structure similar to the active ingredients of opium.

Opium. The sap that exudes from the seed pods of the opium poppy.

Opponent-process theory. The theory that a visual receptor or a neuron signals one color when it responds in one way (e.g., by increasing its firing rate) and signals the complementary color when it responds in the opposite way (e.g., by decreasing its firing rate).

Opsins. Light-sensitive ion channels that are found in the cell membranes of certain bacteria and algae. When opsins are illuminated with light, they open and allow ions to enter the cell.

Optic chiasm. The X-shaped structure on the inferior surface of the diencephalon; the point where the optic nerves decussate.

Optic tectum. The main destination of retinal ganglion cells in nonmammalian vertebrates.

Optogenetics. A method that uses genetic engineering techniques to insert the opsin gene, or variants of the opsin gene, into particular types of neurons. By inserting an opsin gene into a particular type of neuron, a researcher can use light to hyperpolarize or depolarize those neurons.

Orbitofrontal cortex. The cortex of the inferior frontal lobes, adjacent to the orbits, which receives olfactory input from the thalamus.

Orchidectomy. The removal of the testes.

Orexin. A neuropeptide that has been implicated in narcolepsy; sometimes called *hypocretin*.

Organ of Corti. The auditory receptor organ, comprising the basilar membrane, the hair cells, and the tectorial membrane.

Orphan drugs. Drugs for which the market is too small for the necessary developmental research to be profitable.

Orthodromic conduction. Axonal conduction in the normal direction—from the cell body toward the terminal buttons.

Ossicles. The three small bones of the middle ear: the malleus, the incus, and the stapes.

Oval window. The membrane that transfers vibrations from the ossicles to the fluid of the cochlea.

Ovariectomy. The removal of the ovaries.

Ovaries. The female gonads.

Oxytocin. One of the two major peptide hormones of the posterior pituitary, which in females stimulates contractions of the uterus during labor and the ejection of milk during suckling.

Pacinian corpuscles. The largest and most deeply positioned cutaneous receptors, which are sensitive to sudden displacements of the skin.

Paired-image subtraction technique. The use of PET or fMRI to locate constituent cognitive processes in the brain by producing an image of the difference in brain activity associated with two cognitive tasks that differ in terms of a single constituent cognitive process.

Panic attacks. Rapid-onset attacks of extreme fear and severe symptoms of stress (e.g., choking, heart palpitations, shortness of breath).

Panic disorder. An anxiety disorder characterized by recurrent rapid-onset attacks of extreme fear and severe symptoms of stress (choking, heart palpitations, and shortness of breath).

Parallel processing. The simultaneous analysis of a signal in different ways by the multiple parallel pathways of a neural network.

Parasympathetic nerves. Those autonomic motor nerves that project from the brain to the sacral region of the spinal cord.

Paraventricular nuclei. Hypothalamic nuclei that play a role in eating and synthesize hormones released by the posterior pituitary.

Parietal lobe. One of the four cerebral lobes; it is located just posterior to the central fissure.

Parkinson's disease. A movement disorder that is associated with degeneration of dopaminergic neurons in the substantia nigra.

Parvocellular layers. The layers of the lateral geniculate nuclei that are composed of neurons with small cell bodies; the top four layers (also called *P layers*).

Patellar tendon reflex. The stretch reflex that is elicited when the patellar tendon is struck.

Pathogens. Disease-causing agents.

Pattern separation. The ability to separate distinct percepts into individual memories for storage.

Pavlovian conditioning paradigm. A paradigm in which the experimenter pairs an initially neutral stimulus (conditional stimulus) with a stimulus (unconditional stimulus) that elicits a reflexive response (unconditional response); after several pairings, the neutral stimulus elicits a conditional response.

Penumbra. The dysfunctional area of brain tissue around an infarct. The tissue in the penumbra may recover or die in the days following a stroke.

Peptide hormones. Hormones that are short chains of amino acids.

Percept. The outcome of perception.

Perception. The higher-order process of integrating, recognizing, and interpreting complete patterns of sensations.

Perceptual decision making. Decisions affecting perception that are based on prior experiences and current incoming sensory information.

Periaqueductal gray (PAG). The gray matter around the cerebral aqueduct, which contains opiate receptors and activates a descending analgesia circuit.

Perimetry test. The procedure used to map scotomas.

Periodic limb movement disorder. Characterized by periodic, involuntary movements of the limbs often involving twitches of the legs during sleep; one cause of insomnia.

Periodotopy. The notion that auditory cortex topography is linked to the temporal components of sound.

Peripartum depression. The intense, sustained depression experienced by some females during pregnancy, after they give birth, or both.

Peripheral nervous system (PNS). The portion of the nervous system outside the skull and spine.

Perseveration. The tendency to continue making a formerly correct response that is currently incorrect.

Phagocytes. Cells, such as macrophages and microglia, that destroy and ingest pathogens.

Phagocytosis. The destruction and ingestion of foreign matter by cells of the immune system.

Phantom limb. Phenomenon wherein amputees still perceive the presence of their missing limb.

Phantom percepts. Products of perception when there is an absence of sensory input.

Pharmacological. Pertaining to the scientific study of drugs.

Phenothiazines. A class of antipsychotic drugs that bind effectively to both D_1 and D_2 receptors.

Phenotype. An organism's observable traits.

Phenylketonuria (PKU). A neurological disorder whose symptoms are vomiting, seizures, hyperactivity, hyperirritability, intellectual disability, brain damage, and high levels of phenylpyruvic acid in the urine.

Phenylpyruvic acid. A substance that is found in abnormally high concentrations in the urine of those suffering from phenylketonuria.

Pheromones. Chemicals that are released by an animal and elicit through their odor specific patterns of behavior in its conspecifics.

Phoneme. The smallest unit of sound that distinguishes among various words in a language.

Phonetic procedure. A procedure for reading aloud that involves the recognition of letters and the application of a language's rules of pronunciation.

Phonological analysis. Analysis of the sound of language.

Photopic spectral sensitivity curve. The graph of the sensitivity of cone-mediated vision to different wavelengths of light.

Photopic vision. Cone-mediated vision, which predominates when lighting is good.

Phylogeny. The evolutionary development of species.

Physical-dependence theories of addiction. Theories holding that the main factor that motivates drug-addicted individuals to keep taking drugs is the prevention or termination of withdrawal symptoms.

Physically dependent. Being in a state in which the discontinuation of drug taking will induce withdrawal reactions.

Physiological psychology. The division of biopsychology that studies the neural mechanisms of behavior through direct manipulation of the brains of nonhuman animal subjects in controlled experiments.

Pia mater. The delicate, innermost meninx.

Pineal gland. The endocrine gland that is the human body's sole source of melatonin.

Pioneer growth cones. The first growth cones to travel along a particular route in the developing nervous system.

Piriform cortex. An area of medial temporal cortex that is adjacent to the amygdala and that receives direct olfactory input.

Pituitary gland. The gland that dangles from, and is controlled by, the hypothalamus.

Pituitary peptides. One of the five categories of neuropeptide transmitters; it contains neuropeptides that were first identified as hormones released by the pituitary.

Pituitary stalk. The structure connecting the hypothalamus and the pituitary gland.

Place cells. Neurons that respond only when the subject is in specific locations (i.e., in the place fields of the neurons).

Planum temporale. An area of temporal lobe cortex that lies in the posterior region of the lateral fissure and, in the left hemisphere, roughly corresponds to Wernicke's area.

Plethysmography. Any technique for measuring changes in the volume of blood in a part of the body.

Pluripotent. Cells that can develop into many, but not all, classes of body cells.

Polarized. In the context of membrane potentials, it is a membrane potential that is not zero.

Polyandry. A pattern of mate bonding in which one female bonds with more than one male.

Polygraphy. A method of interrogation that employs ANS indexes of emotion to infer the truthfulness of a person's responses.

Polygyny. A pattern of mate bonding in which one male bonds with more than one female; the most prevalent pattern of mate bonding in mammals.

Polyphasic sleep cycles. Sleep cycles that regularly involve more than one period of sleep per day.

Pons. The metencephalic structure that creates a bulge on the ventral surface of the brain stem.

Positive symptoms. Symptoms of schizophrenia that seem to represent an excess of typical function.

Positive-incentive theories of addiction. Theories holding that the primary factor in most cases of addiction is the craving for the positive-incentive (expected pleasure-producing) properties of the drug.

Positive-incentive theory. The idea that behaviors (e.g., eating and drinking) are motivated by their anticipated pleasurable effects.

Positive-incentive value. The anticipated pleasure associated with a particular action, such as taking a drug.

Positron emission tomography (PET). A technique for visualizing brain activity, usually by measuring the accumulation of radioactive fluorodeoxyglucose (FDG) in active areas of the brain.

Postcentral gyrus. The gyrus located just posterior to the central fissure; its function is primarily somatosensory.

Posterior. Toward the tail end of a vertebrate or toward the back of the head.

Posterior parietal association cortex. An area of association cortex that receives input from the visual, auditory, and somatosensory systems and is involved in the perception of spatial location and guidance of voluntary behavior.

Posterior parietal cortex. The posterior area of the parietal cortex.

Posterior pituitary. The part of the pituitary gland that contains the terminals of hypothalamic neurons.

Postnatal period. The period of development after birth.

Postsynaptic potentials. Potentials that move the postsynaptic cell's membrane potential away from the resting state.

Posttraumatic amnesia (PTA). Amnesia produced by a nonpenetrating head injury (a blow to the head that does not penetrate the skull).

Prader-Willi syndrome. A neurodevelopmental disorder that is characterized by insatiable appetite and exceptionally slow metabolism.

Precentral gyrus. The gyrus located just anterior to the central fissure; its function is primarily motor.

Prefrontal cortex. The areas of frontal cortex that are anterior to the frontal motor areas.

Prefrontal lobes. Areas of cortex, left and right, that are located at the very front of the brain—in the frontal lobes.

Prefrontal lobotomy. A surgical procedure in which the connections between the prefrontal lobes and the rest of the brain are cut, as a treatment for mental illness.

Premotor cortex. The area of secondary motor cortex that lies between the supplementary motor area and the lateral fissure.

Prenatal period. The period of development before birth.

Prestriate cortex. The band of tissue in the occipital lobe that surrounds the primary visual cortex and contains areas of secondary visual cortex.

Primary motor cortex. The cortex of the precentral gyrus, which is the major point of departure for motor signals descending from the cerebral cortex into lower levels of the sensorimotor system.

Primary sensory cortex. An area of sensory cortex that receives most of its input directly from the thalamic relay nuclei of one sensory system.

Primary visual cortex. The area of the cortex that receives direct input from the lateral geniculate nuclei (also called *striate cortex*).

Primates. One of 20 different orders of mammals; there are about a dozen families of primates.

Proceptive behaviors. Behaviors that solicit the sexual advances of members of the other sex.

Progesterone. A progestin that prepares the uterus and breasts for pregnancy.

Progestins. The class of steroid hormones that includes progesterone.

Promoters. Stretches of DNA whose function is to determine whether or not particular structural genes are converted into proteins through the process of gene expression.

Prosopagnosia. Visual agnosia for faces.

Protein hormones. Hormones that are long chains of amino acids.

Proteins. Long chains of amino acids.

Proximal. Close to something.

Proximal segment. The segment of a cut axon between the cut and the cell body.

Psychedelic drugs. Drugs whose primary action is to alter perception, emotion, and cognition.

Psychiatric disorder. A disorder of psychological function sufficiently severe to require treatment by a psychiatrist or clinical psychologist.

Psychoactive drugs. Drugs that influence subjective experience and behavior by acting on the nervous system.

Psychoneuroimmunology. The study of interactions among psychological factors, the nervous system, and the immune system.

Psychopharmacology. The division of biopsychology that studies the effects of drugs on the brain and behavior.

Psychophysiology. The division of biopsychology that studies the relation between physiological activity and psychological processes in human subjects by noninvasive methods.

Psychosis. A loss of touch with reality.

Psychosomatic disorder. Any physical disorder that can be caused or exacerbated by stress.

Psychosurgery. Any brain surgery performed for the treatment of a psychological problem (e.g., prefrontal lobotomy).

P300 wave. The positive EEG wave that usually occurs about 300 milliseconds after a momentary stimulus that has meaning for the subject.

Pulsatile hormone release. The typical pattern of hormone release: Hormones are discharged several times per day in large surges.

Pure research. Research motivated primarily by the curiosity of the researcher and done solely for the purpose of acquiring knowledge.

Purkinje effect. In intense light, red and yellow wavelengths look brighter than blue or green wavelengths of equal intensity; in dim light, blue and green wavelengths look brighter than red and yellow wavelengths of equal intensity.

Putamen. A structure that is joined to the caudate by a series of fiber bridges; together the putamen and caudate compose the striatum.

Pyramidal cell layer. One of the major layers of cell bodies in the hippocampus.

Pyramidal cells. Large multipolar cortical neurons with a pyramid-shaped cell body, an apical dendrite, and a very long axon.

Quasiexperimental studies. Studies of groups of subjects who have been exposed to the conditions of interest in the real world; such studies have the appearance of experiments but are not true experiments because potential confounded variables have not been controlled for.

Radial arm maze. A maze in which several arms radiate out from a central starting chamber; commonly used to study spatial learning in rats.

Radial arm maze test. A widely used test of rats' spatial ability in which the same arms are baited on each trial, and the rats must learn to visit only the baited arms once per trial.

Radial glial cells. Glial cells that exist in the neural tube during the period of neural migration and that form a network along which radial migration occurs. Some radial glial cells are stem cells.

Radial migration. Movement of cells in the developing neural tube from the ventricular zone in a straight line outward toward the tube's outer wall.

Reactive depression. Depression that is triggered by a negative experience.

Reappraisal paradigm. An experimental method for studying emotion; subjects are asked to reinterpret a film or photo to change their emotional reaction to it while their brain activity is recorded.

Receptive. Pertaining to the comprehension of language and speech.

Receptive field. The area of the visual field within which it is possible for the appropriate stimulus to influence the firing of a visual neuron.

Receptor blockers. Antagonistic drugs that bind to postsynaptic receptors without activating them and block the access of the usual neurotransmitter.

Receptor subtypes. The different types of receptors to which a particular neurotransmitter can bind.

Receptors. Cells that are specialized to receive chemical, mechanical, or radiant signals from the environment; also proteins that contain binding sites for particular neurotransmitters.

Recessive trait. The trait of a dichotomous pair that is not expressed in the phenotype of heterozygous individuals.

Reciprocal innervation. The principle of spinal cord circuitry that causes a muscle to automatically relax when a muscle that is antagonistic to it contracts.

Recuperation theories of sleep. Theories based on the premise that being awake disturbs the body's homeostasis and the function of sleep is to restore it.

Recurrent collateral inhibition. The inhibition of a neuron that is produced by its own activity via a collateral branch of its axon and an inhibitory interneuron.

Red nucleus. A structure of the sensorimotor system that is located in the tegmentum of the mesencephalon.

Reference memory. Memory for the general principles and skills that are required to perform a task.

Relapse. The return to one's drug taking habit after a period of voluntary abstinence.

Relative refractory period. A period after the absolute refractory period during which a higher-than-normal amount of stimulation is necessary to make a neuron fire.

Release-inhibiting hormones. Hypothalamic hormones that inhibit the release of hormones from the anterior pituitary.

Releasing hormones. Hypothalamic hormones that stimulate the release of hormones from the anterior pituitary.

REM sleep. The stage of sleep characterized by rapid eye movements, loss of core muscle tone, and emergent stage 1 EEG.

REM-sleep behavior disorder. A disorder where the individual experiences REM sleep without core-muscle atonia.

Remote memory. Memory for experiences in the distant past.

Repetition priming tests. Tests of implicit memory; in one example, a list of words is presented, then fragments of the original words are presented and the subject is asked to complete them.

Repetitive transcranial magnetic stimulation (rTMS). A form of transcranial magnetic stimulation (TMS) that involves the delivery of repetitive magnetic pulses at either high frequencies (e.g., five pulses per second; high-frequency rTMS) or low frequencies (e.g., less than one pulse per second; low-frequency rTMS) to specific cortical areas.

Replacement injections. Injections of a hormone whose natural release has been curtailed by the removal of the gland that normally releases it.

Replication. The process by which the DNA molecule duplicates itself.

Repressors. Proteins that bind to DNA and decrease gene expression.

Reserpine. The first monoamine antagonist to be used in the treatment of schizophrenia; the active ingredient of the snakeroot plant.

Response-chunking hypothesis. The idea that practice combines the central sensorimotor programs that control individual responses into programs that control sequences (chunks) of behavior.

Resting potential. The steady membrane potential of a neuron at rest, usually about −70 mV.

Resting state-fMRI. One application of functional magnetic resonance imaging (fMRI) wherein brain scans are carried out while the participant is not performing any explicit tasks.

Restless legs syndrome. Tension or uneasiness in the legs that keeps a person from falling asleep; one cause of insomnia.

Reticular activating system. The hypothetical arousal system in the reticular formation.

Retina-geniculate-striate pathway. The major visual pathway from each retina to the striate cortex (primary visual cortex) via the lateral geniculate nuclei of the thalamus.

Retinal ganglion cells. Retinal neurons whose axons leave the eyeball and form the optic nerve.

Retinex theory. Land's theory that the color of an object is determined by its reflectance, which the visual system calculates by comparing the ability of adjacent surfaces to reflect short, medium, and long wavelengths.

Retinotopic. Organized, like the primary visual cortex, according to a map of the retina.

Retrograde amnesia. Loss of memory for events or information learned before the amnesia-inducing brain injury.

Retrograde degeneration. Degeneration of the proximal segment of a cut axon.

Reuptake. The drawing back into the terminal button of neurotransmitter molecules after their release into the synapse; the most common mechanism for deactivating a released neurotransmitter.

Reversible lesions. Methods for temporarily eliminating the activity in a particular area of the brain while tests are being conducted.

Rhodopsin. The photopigment of rods.

Ribonucleic acid (RNA). A molecule that is similar to DNA except that it has the nucleotide base uracil and a phosphate and ribose backbone.

Ribosome. Intracellular structures found in large numbers in the cytoplasm of living cells. They are involved in the translation phase of gene expression.

Risk-assessment test. An animal model of anxiety. After a single brief exposure to a cat on the surface of a laboratory burrow system, rats flee to their burrows and freeze. Then they engage in a variety of risk-assessment behaviors.

RNA editing. An epigenetic mechanism wherein messenger RNA is modified through the actions of small RNA molecules and other proteins.

Rods. The visual receptors in the retina that mediate achromatic, low-acuity vision under dim light.

Rubber-hand illusion. The feeling that an extraneous object, usually a rubber hand, is actually part of one's own body.

Saccades. The rapid movements of the eyes between fixations.

Sagittal sections. Any slices of brain tissue cut in a plane that is parallel to the side of the brain.

Saltatory conduction. Conduction of an action potential from one node of Ranvier to the next along a myelinated axon.

Satiety. The motivational state that terminates a meal when there is food remaining.

Savants. Individuals with developmental disabilities who nevertheless display amazing and specific cognitive or artistic abilities; savant abilities are sometimes associated with autism spectrum disorder.

Schwann cells. The glial cells that compose the myelin sheaths of PNS axons and promote the regeneration of PNS axons.

Scientific inference. The logical process by which observable events are used to infer the properties of unobservable events.

Scotoma. An area of blindness produced by damage to, or disruption of, an area of the visual system.

Scotopic spectral sensitivity curve. The graph of the sensitivity of rod-mediated vision to different wavelengths of light.

Scotopic vision. Rod-mediated vision, which predominates in dim light.

Scrotum. The sac that holds the male testes outside the body cavity.

Seasonal affective disorder (SAD). Type of major depressive disorder in which episodes of depression typically recur during particular seasons—usually during the winter months.

Second messenger. A chemical synthesized in a neuron in response to the binding of a neurotransmitter to a metabotropic receptor in its cell membrane.

Secondary motor cortex. An area of the cerebral cortex that receives much of its input from association cortex and sends much of its output to primary motor cortex.

Secondary sensory cortex. An area of sensory cortex that receives most of its input from the primary sensory cortex of one sensory system or from other areas of secondary cortex of the same system.

Secondary sex characteristics. Body features, other than the reproductive organs, that distinguish males from females.

Secondary visual cortex. Areas of cerebral cortex that receive most of their input from primary visual cortex.

Selective attention. The ability to focus on a small subset of the multitude of stimuli that are being received at any one time.

Selective serotonin-reuptake inhibitors (SSRIs). Class of drugs that exert agonistic effects by blocking the reuptake of serotonin from synapses; typically used to treat depression.

Self-stimulation paradigm. A paradigm in which animals press a lever to administer reinforcing electrical stimulation to particular sites in their own brains.

Semantic analysis. Analysis of the meaning of language.

Semantic memories. Explicit memories for general facts or knowledge.

Semicircular canals. The receptive organs of the vestibular system.

Sensation. The process of detecting the presence of stimuli.

Sensitive period. An interval of time during development when an experience can have a greater effect on development if it occurs during that interval, as opposed to outside that interval.

Sensitivity. In vision, the ability to detect the presence of dimly lit objects.

Sensorimotor phase. The second of the two phases of birdsong development, during which juvenile birds progress from subsongs to adult songs.

Sensory evoked potential. A change in the electrical activity of the brain (e.g., in the cortical EEG) that is elicited by the momentary presentation of a sensory stimulus.

Sensory feedback. Sensory signals that are produced by a response and are often used to guide the continuation of the response.

Sensory phase. The first of the two phases of birdsong development, during which young birds do not sing but form memories of the adult songs they hear.

Sensory relay nuclei. Those nuclei of the thalamus whose main function is to relay sensory signals to the appropriate areas of cortex.

Sensory-specific satiety. The fact that the consumption of a particular food produces greater satiety for foods of the same taste than for other foods.

Septum. A midline nucleus of the limbic system, located near the anterior tip of the cingulate cortex.

Serotonin. An indolamine neurotransmitter; the only member of this class of monoamine neurotransmitters found in the mammalian nervous system.

Set point. The value of a physiological parameter that is maintained constantly by physiological or behavioral mechanisms; for example, the body's energy resources are often assumed to be maintained at a constant optimal level by compensatory changes in hunger.

Set-point assumption. The assumption that hunger is typically triggered by a decline in the body's energy reserves below their set point.

Settling point. The point at which various factors that influence the level of some regulated function (such as body weight) achieve an equilibrium.

Sex chromosomes. The pair of chromosomes that determine an individual's genetic sex: XX for a female and XY for a male.

Sex-linked traits. Traits that are influenced by genes on the sex chromosomes.

Sexual dimorphisms. Instances where a behavior (or structure) comes in two distinct classes (male or female) into which most individuals can be unambiguously assigned.

Sexually dimorphic nucleus. The nucleus in the medial preoptic area of rats that is larger in males than in females.

Sham eating. The experimental protocol in which an animal chews and swallows food, after which the food immediately exits its body through a tube implanted in its esophagus.

Sham rage. The exaggerated, poorly directed aggressive responses of decorticate animals.

Short-term memory. Storage of information for brief periods of time while a person attends to it.

Signal averaging. A method of increasing the signal-to-noise ratio by reducing background noise.

Simple cells. Neurons in the visual cortex that respond maximally to straight-edge stimuli of a particular width and orientation.

Simple seizures. Focal seizures in which the symptoms are primarily sensory or motor or both.

Simultanagnosia. A difficulty attending to more than one stimulus at a time.

Sinestrals. Left-handers.

Skeletal muscle (extrafusal muscle). Striated muscle that is attached to the skeleton and is usually under voluntary control.

Skin conductance level (SCL). A measure of the background level of skin conductance associated with a particular situation.

Skin conductance response (SCR). The transient change in skin conductance associated with discrete experiences.

Sleep apnea. A condition in which sleep is repeatedly disturbed by momentary interruptions in breathing.

Sleep inertia. The unpleasant feeling of grogginess that is sometimes experienced for a few minutes after awakening.

Sleep paralysis. A sleep disorder characterized by the inability to move (paralysis) just as a person is falling asleep or waking up.

Slow-wave sleep (SWS). Stage 3 sleep, which is characterized by the largest and slowest EEG waves.

Smoking. Inhaling the smoke from the burning of tobacco.

Smoker's syndrome. The chest pain, labored breathing, wheezing, coughing, and heightened susceptibility to infections of the respiratory tract commonly observed in tobacco smokers.

Sodium amytal test. A test involving the anesthetization of first one cerebral hemisphere and then the other to determine which hemisphere plays the dominant role in language.

Sodium–potassium pumps. An ion transporter that actively exchanges three Na^+ ions inside the neuron for two K^+ ions outside.

Solitary nucleus. The medullary relay nucleus of the gustatory system.

Soluble-gas neurotransmitters. A class of unconventional neurotransmitters that includes nitric oxide and carbon monoxide.

Somal translocation. One of two major modes of neural migration, in which an extension grows out from the undeveloped neuron and draws the cell body up into it.

Somatic nervous system (SNS). The part of the peripheral nervous system that interacts with the external environment.

Somatosensory homunculus. The somatotopic map in the primary somatosensory cortex.

Somatotopic. Organized, like the primary somatosensory cortex, according to a map of the surface of the body.

Spandrels. Incidental nonadaptive evolutionary by-products of some adaptive characteristic.

Spatial resolution. Ability of a recording technique to detect differences in spatial location (e.g., to pinpoint a location in the brain).

Spatial summation. The integration of signals that originate at different sites on the neuron's membrane.

Species. A group of organisms that is reproductively isolated from other organisms; the members of one species cannot produce fertile offspring by mating with members of other species.

Species-common behaviors. Behaviors that are displayed in the same manner by virtually all like members of a species.

Specific phobia. An anxiety disorder that involves strong fear or anxiety about particular objects (e.g., birds, spiders) or situations (e.g., enclosed spaces, darkness).

Spindle afferent neurons. Neurons that carry signals from muscle spindles into the spinal cord via the dorsal root.

Split-brain patients. Commissurotomized patients.

Sry gene. A gene on the Y chromosome that triggers the production of Sry protein.

Sry protein. A protein that causes the medulla of each primordial gonad to grow and develop into a testis.

Standard consolidation theory. The theory that memories are temporarily stored in the hippocampus until they can be transferred to a more stable cortical storage system. Also known as *dual-trace theory*.

Static phase. The second phase of the VMH syndrome, during which the obese animal maintains a stable level of obesity.

Stellate cells. Small star-shaped cortical interneurons.

Stem cells. Cells that have an almost unlimited capacity for self-renewal and the ability to develop into many different types of cells.

Stereognosis. The process of identifying objects by touch.

Stereotaxic atlas. A series of maps representing the three-dimensional structure of the brain that is used to determine coordinates for stereotaxic surgery.

Stereotaxic instrument. A device for performing stereotaxic surgery, composed of two parts: a head holder and an electrode holder.

Steroid hormones. Hormones that are synthesized from cholesterol.

Stimulants. Drugs that produce general increases in neural and behavioral activity.

Stress. The physiological changes that occur when the body is exposed to harm or threat.

Stressors. Experiences that induce a stress response.

Stretch reflex. A reflexive counteracting reaction to an unanticipated external stretching force on a muscle.

Striatum. A structure of the basal ganglia that is the terminal of the dopaminergic nigrostriatal pathway.

Strokes. Sudden-onset cerebrovascular disorders that cause brain damage.

Subarachnoid space. The space beneath the arachnoid membrane, which contains many large blood vessels and cerebrospinal fluid.

Subcutaneous fat. Fat stored under the skin.

Subordination stress. Stress experienced by animals, typically males, that are continually attacked by higher-ranking conspecifics.

Substantia nigra. The midbrain nucleus whose neurons project via the nigrostriatal pathway to the striatum of the basal ganglia; it is part of the mesotelencephalic dopamine system.

Subthalamic nucleus. A nucleus that lies just below the thalamus and is connected to the basal ganglia; deep brain stimulation applied to this site has been used to treat Parkinson's disease.

Subventricular zone. A region adjacent to the ventricular zone; the ventricular zone is adjacent to the ventricles.

Sulci. Small furrows in a convoluted cortex.

Superior. Toward the top of the primate head.

Superior colliculi. Two of the four nuclei that compose the tectum; they receive major visual input.

Superior olives. Medullary nuclei that play a role in sound localization.

Superior temporal gyri. The plural of superior temporal gyrus.

Superior temporal gyrus. The large gyrus of the temporal lobe adjacent to the lateral fissure; the location of auditory cortex.

Supplementary motor area. The area of secondary motor cortex that is within and adjacent to the longitudinal fissure.

Suppression paradigm. An experimental method for studying emotion; subjects are asked to inhibit their emotional reactions to unpleasant films or photos while their brain activity is recorded.

Suprachiasmatic nuclei (SCN). Nuclei of the medial hypothalamus that control the circadian cycles of various body functions.

Supraoptic nuclei. Hypothalamic nuclei in which the hormones of the posterior pituitary are synthesized.

Surface dyslexia. A reading disorder in which the lexical procedure is disrupted while the phonetic procedure is not.

Surface interpolation. The process by which we perceive surfaces; the visual system extracts information about edges and from it infers the appearance of large surfaces.

Sympathetic nerves. Those motor nerves of the autonomic nervous system that project from the central nervous system in the lumbar and thoracic region areas of the spinal cord.

Synaptic vesicles. Small spherical membranes that store neurotransmitter molecules and release them into the synaptic cleft.

Synaptogenesis. The formation of new synapses.

Synergistic muscles. Pairs of muscles whose contraction produces a movement in the same direction.

T cells. T lymphocytes; lymphocytes that bind to foreign micro-organisms and cells that contain them and, in so doing, destroy them.

Tangential migration. Movement of cells in the developing neural tube in a direction parallel to the tube's walls.

Tardive dyskinesia (TD). A motor disorder that results from chronic use of certain antipsychotic drugs.

Target-site concept. The idea that aggressive and defensive behaviors of an animal are often designed to attack specific sites on the body of another animal while protecting specific sites on its own.

Taste buds. Clusters of taste receptors found on the tongue and in parts of the oral cavity.

Tau. The first circadian gene to be identified in mammals.

Tau protein. Plays a role in maintaining the overall structure of neurons.

Tectorial membrane. The cochlear membrane that rests on the hair cells.

Tegmentum. The ventral division of the mesencephalon; it includes part of the reticular formation, substantia nigra, and red nucleus.

Telencephalon. The most superior of the brain's five major divisions.

Temporal hemiretina. The half of each retina next to the temple.

Temporal lobe. One of the four major cerebral lobes; it lies adjacent to the temples and contains the hippocampus and amygdala.

Temporal resolution. Ability of a recording technique to detect differences in time (i.e., to pinpoint when an event occurred).

Temporal summation. The integration of neural signals that occur at different times at the same synapse.

Teratogen. A drug or other chemical that causes birth defects.

Testes. The male gonads.

Testosterone. The most common androgen.

Thalamus. The large two-lobed diencephalic structure that constitutes the anterior end of the brain stem; many of its nuclei are sensory relay nuclei that project to the cortex.

THC. Delta-9-tetrahydrocannabinol, the main psychoactive constituent of marijuana.

Thermal grid illusion. The perception of pain that results from placing one's hand on a grid of metal rods that alternate between cool and warm.

Thigmotaxic. Tending to stay near the walls of an open space such as a test chamber.

Thinking creatively. Thinking in productive, unconventional ways.

Threshold of excitation. The level of depolarization necessary to generate an action potential; usually about −65 mV.

Thrombosis. The blockage of blood flow by a plug (a thrombus) at the site of its formation.

Thyrotropin. The anterior pituitary hormone that stimulates the release of hormones from the thyroid gland.

Thyrotropin-releasing hormone. The hypothalamic hormone that stimulates the release of thyrotropin from the anterior pituitary.

Tics. Involuntary, repetitive, stereotyped movements or vocalizations; the defining feature of Tourette's disorder.

Tinnitus. Ringing in the ears.

Token test. A preliminary test for language-related deficits that involves following verbal instructions to touch or move tokens of different shapes, sizes, and colors.

Toll-like receptors. Receptors found in the cell membranes of many cells of the innate immune system; they trigger phagocytosis and inflammatory responses.

Tonic-clonic seizure. A type of generalized seizure whose primary behavioral symptoms are loss of consciousness, loss of equilibrium, and a tonic-clonic convulsion—a convulsion involving both tonus and clonus.

Tonotopic. Organized, like the primary auditory cortex, according to the frequency of sound.

Top-down. A sort of neural mechanism that involves activation of lower cortical areas by higher cortical areas.

Topographic gradient hypothesis. The hypothesis that axonal growth is guided by the relative position of the cell bodies on intersecting gradients, rather than by point-to-point coding of neural connections.

Totipotent. Capable of developing into any type of body cell.

Tourette's disorder. A disorder of tics (involuntary, repetitive, stereotyped movements or vocalizations).

Toxic psychosis. A chronic psychiatric disorder produced by exposure to a neurotoxin.

Tracts. Bundles of axons in the central nervous system.

Transcranial electrical stimulation. A technique that can be used to stimulate ("turn on") an area of the cortex by applying an electrical current through two electrodes placed directly on the scalp.

Transcranial magnetic stimulation (TMS). A technique that can be used to stimulate ("turn on") or turn off an area of the cortex by creating a magnetic field under a coil positioned next to the skull.

Transcranial ultrasound stimulation. A technique that, like transcranial electrical stimulation and magnetic stimulation, can be used to activate particular brain structures.

Transcription. The first phase of gene expression, wherein a strand of messenger RNA (mRNA) is transcribed from one of the exposed DNA strands and carries the genetic code from the nucleus into the cytoplasm of the cell.

Transcription factors. Intracellular proteins that bind to DNA and influence the operation of particular genes.

Transduction. The conversion of one form of energy to another.

Transfer RNA. Molecules of RNA that carry amino acids to ribosomes during protein synthesis; each kind of amino acid is carried by a different kind of transfer RNA molecule.

Transgender. An individual who identifies as a man, a woman, or some intersection thereof.

Transgenerational epigenetics. A subfield of epigenetics that examines the transmission of experiences via epigenetic mechanisms across generations.

Transgenic mice. Mice into which the genetic material of another species has been introduced.

Translation. The second phase of gene expression, wherein the strand of messenger RNA (mRNA) is converted by a ribosome and transfer RNA (tRNA) into a protein.

Transient global amnesia. A sudden onset severe anterograde amnesia and moderate retrograde amnesia for explicit episodic memory that is transient—typically lasting only between 4 to 6 hours.

Translational bottleneck. A barrier keeping promising ideas and treatments from becoming the focus of translational research; largely created by the massive cost of such research.

Translational research. Research designed to translate basic scientific discoveries into effective applications (e.g., into clinical treatments).

Transneuronal degeneration. Degeneration of a neuron caused by damage to another neuron to which it is linked by a synapse.

Transorbital lobotomy. A prefrontal lobotomy performed with an instrument inserted through the eye socket.

Transporters. Mechanisms in the membrane of a cell that actively transport ions or molecules across the membrane.

Traumatic brain injury. Serious damage caused to the brain by a blow to the head.

Tricyclic antidepressants. Drugs with an antidepressant action and a three-ring molecular structure.

Tripartite synapse. A synapse that involves two neurons and an astroglia.

True-breeding lines. Breeding lines in which interbred members always produce offspring with the same trait, generation after generation.

Tumor (neoplasm). A mass of cells that grows independently of the rest of the body.

Tympanic membrane. The eardrum.

Typical antipsychotics. The first generation of antipsychotic drugs.

Unipolar neuron. A neuron with one process extending from its cell body.

Unipotent. Cells that can develop into only one type of cell.

Up-regulation. An increase in the number of receptors for a neurotransmitter in response to decreased release of that neurotransmitter.

Urbach-Wiethe disease. A genetic disorder that often results in the calcification of the amygdala and surrounding brain structures.

Vaccination. Administering a weakened form of a virus so that if the virus later invades, the adaptive immune system is prepared to deal with it.

Vaping. Inhaling a vapor that contains nicotine.

Vasopressin. One of the two major peptide hormones of the posterior pituitary; it facilitates reabsorption of water by kidneys and is thus also called *antidiuretic hormone*.

Ventral. Toward the chest surface of a vertebrate or toward the bottom of the head.

Ventral horns. The two ventral arms of the spinal gray matter.

Ventral posterior nucleus. A thalamic relay nucleus in both the somatosensory and gustatory systems.

Ventral stream. The group of visual pathways that flows from the primary visual cortex to the ventral prestriate cortex to the inferotemporal cortex.

Ventral tegmental area. The midbrain nucleus of the mesotelencephalic dopamine system that is the major source of the mesoscorticolimbic pathway.

Ventricular zone. The region adjacent to the ventricle in the developing neural tube.

Ventromedial hypothalamus (VMH). The area of the hypothalamus that was once thought to be a satiety center.

Ventromedial nucleus (VMN). A hypothalamic nucleus that is thought to be involved in female sexual behavior.

Vertebrates. Chordates that possess spinal bones.

Vestibular system. The sensory system that detects changes in the direction and intensity of head movements and that contributes to the maintenance of balance through its output to the motor system.

Visceral fat. Fat stored around the internal organs of the body cavity.

Visual agnosia. A failure to recognize visual stimuli that is not attributable to sensory, verbal, or intellectual impairment.

Visual association cortex. Areas of cerebral cortex that receive input from areas of secondary visual cortex as well as from secondary areas of other sensory systems.

Visual completion. The completion or filling in of a scotoma by the brain.

Voltage-activated ion channels. Ion channels that open and close in response to changes in the level of the membrane potential.

Wechsler Adult Intelligence Scale (WAIS). A widely used test of general intelligence that includes 11 subtests.

Wernicke-Geschwind model. An influential model of cortical language localization in the left hemisphere.

Wernicke's aphasia. A hypothetical disorder of language comprehension with no associated deficits in speech production.

Wernicke's area. The area of the left temporal cortex hypothesized by Wernicke to be the center of language comprehension.

"Where" versus "what" theory. The theory that the dorsal stream mediates the perception of where things are and the ventral stream mediates the perception of what things are.

White matter. Portions of the nervous system that are white because they are composed largely of myelinated axons.

Williams syndrome. A neurodevelopmental disorder characterized by intellectual disability, accompanied by preserved language and social skills.

Withdrawal reflex. The reflexive withdrawal of a limb when it comes in contact with a painful stimulus.

Withdrawal syndrome. The illness brought on by the elimination from the body of a drug on which the person is physically dependent.

Within-subjects design. An experimental design in which the same subjects are tested under each condition.

Wolffian system. The embryonic precursor of the male reproductive ducts.

Working memory. Temporary memory that is necessary for the successful performance of a task on which one is currently working.

Zeitgebers. Environmental cues, such as the light–dark cycle, that entrain circadian rhythms.

Zeitgeist. The general intellectual climate of a culture.

Zygote. The cell formed from the amalgamation of a sperm cell and an ovum.

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